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Prototype remote vehicle diagnostics for police cruisers

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PROTOTYPE REMOTE VEHICLE DIAGNOSTICS FOR POLICE CRUISERS

By

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LIST OF ACRONYMS

CATLab	Consolidated Advanced Technologies for Law Enforcement Laboratory
CDF	Cumulative Distribution Function
DSP	Digital Signal Processing
DTC	Diagnostics Trouble Code
ECU	Engine Control Unit
EOL	End of Life
EPA	Environmental Protection Agency
FCC	Federal Communications Commission
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
GPH	Gallons per Hour
GPS	Global Positing System
GUI	Graphical User Interface
IDB	Intelligent Transportation System Data Bus
ISO	International Organization for Standardization
MIL	Malfunction Indicator Lamp
MPG	Miles per Gallon
MPH	Miles per Hour
NHSP	New Hampshire State Police
OBD	Onboard-Diagnostics
PCM	Power Control Module

PDF	Probability Density Function
PID	Parameter Identification
PWM	Pulse Width Modulation
RFM	Remote Fleet Management
RPM	Revolutions per Minute
RVD	Remote Vehicle Diagnostics
SAE	Society of Automotive Engineers
VPW	Variable Pulse Width Modulation

ABSTRACT

PROTOTYPE REMOTE VEHICLE DIAGNOSTICS FOR POLICE CRUISERS

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The goal of this thesis was to suggest ways of evaluating the health of police cruisers without bringing these cruisers into a repair facility. The prototype in-car application was developed. The hardware connection was made between the in-car network and the Project54 network. The software was built to collect, process, and send the vehicle information to the server via a telecommunication tool. The prototype in-car application was tested in simulation and on the road. After the development of the prototype in-car application, the radio traffic research gives a few recommended methods for sending the car health information in the New Hampshire Department of Safety radio. The police radio was monitored and interpreted. The gathered radio traffic data was modeled in different perspectives. The recommendations were made based on simulation.

CHAPTER 1
INTRODUCTION

1.1 Introduction

Vehicle telematics systems are popular thanks to today's high speed wireless communication technology. A vehicle telematics system is a system integrating telecommunication tools to send, receive, and store information. The vehicle telematics systems are used to track the location of fleets of vehicles, to notify emergency responders about a collision, to recover stolen vehicles, and so on. One vehicle telematics system is Remote Vehicle Diagnostics (RVD) which is a system that maintains a fleet of cars wirelessly. This thesis details the prototype RVD application in the existing Project54 system.

The Consolidated Advanced Technologies for Law Enforcement Laboratory (CATLab) at UNH has developed the Project54 system. The Project54 system is both an in-car and a telematics system to help a police officer's work in the field. The Project54 in-car system integrates all police equipment such as radar, lights and siren, and video units into one system. The integration creates an organized control environment so a police officer can focus on driving. Figure 1.1 shows the Project54 hardware integration. All police equipment is connected to the Intelligent Transportation System Data Bus (IDB) [1]. The officer can interact with the Projec54 system using a LCD touch screen, keyboard and mouse, PDA, and voice command.

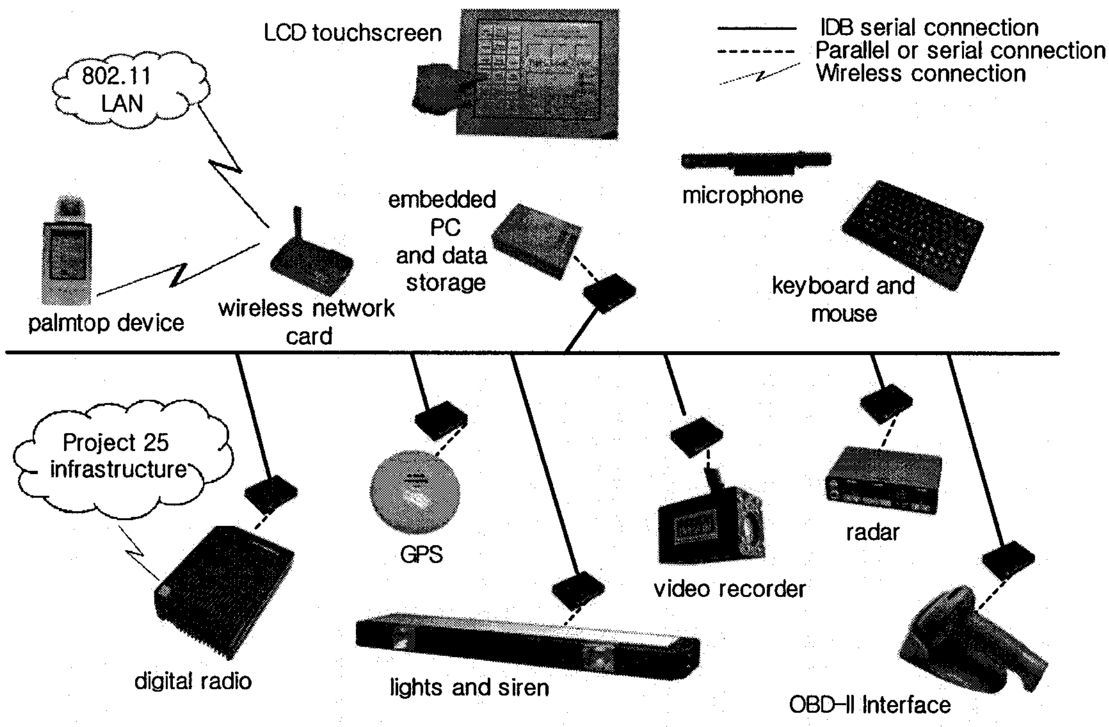
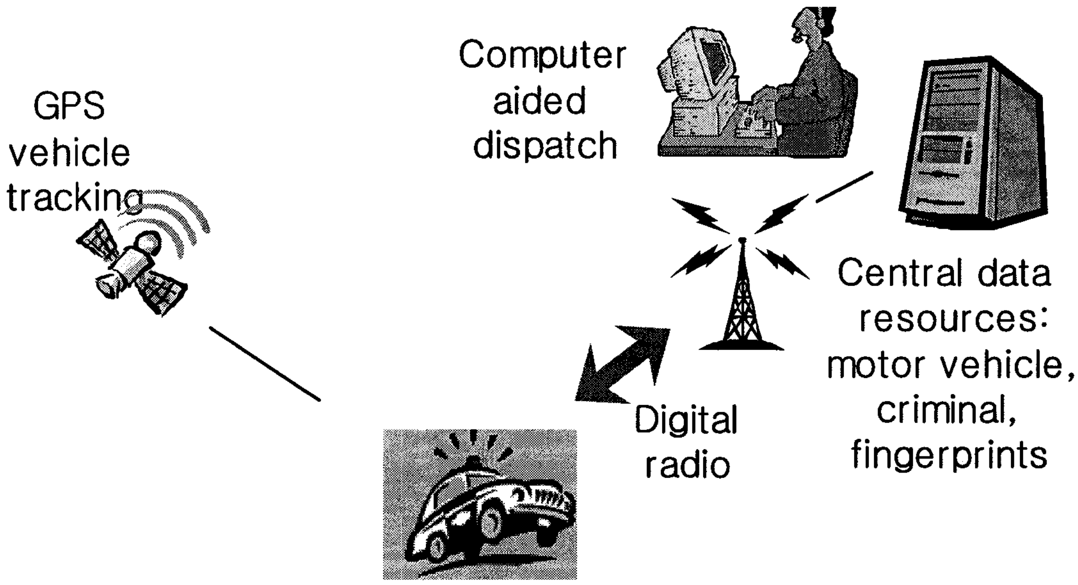


Figure 1.1 A Project54 In-car System

An existing telematics system in Project54 assists a police officer. It provides digital information to check the vehicle record, the driver's license, and the criminal check from the central database via the police radio [2]. It can also provide the location of the cruiser to both headquarters and the individual unit with Global Positioning System (GPS) information (Figure 1.2). However, the current Project54 telematics system does not utilize the full capacity of the telematics that can offer police officers many benefits.



Figure

Figure 1.2 An Existing Project54 Telematics System

RVD is an increasingly popular telematics system that inspects a group of vehicles wirelessly. RVD is used for many purposes: scheduling maintenance, remotely diagnosing vehicle problems, and reporting the condition of vehicles. This technology is expected to provide increased officer safety, efficient work environments, and financial savings for law enforcement fleets. Automated vehicle diagnosis increases the safety of police officers with the ability to notify headquarters about a vehicle accident. Efficiency would be improved since potential damage can be detected and fixed before an actual breakdown of a vehicle. Costs would be reduced since the labor required to collect and update vehicle status for police cruisers would be reduced.

1.2 Problems

The problem is that currently the New Hampshire Department of Safety (NHDS) does not have a way to assess the health of its police cruisers without bringing these cruisers into a repair facility. Police cruisers must be well maintained since police officers often encounter dangerous situations when they are in the vehicles. A constant care to keep the good condition of police cruisers is an important job to guarantee the safety of police officers. However, constant manual labor that inspects many vehicles costs a lot for the NHDS. In addition to the problem of evaluating the health of police cruisers, there is no automated system to notify police headquarters when a police cruiser gets into an accident. This accident report provides critical information for the safety of police officers.

The second problem is that we do not know whether the NHDS radio provides a sufficient bandwidth to transmit vehicle health information over it at a reasonable rate. Currently, NHDS radio is a conventional police radio which utilizes only one channel for police officers in one area. The channel may not be available to transmit vehicle health information when a lot of voice and data transmissions simultaneously exist in the radio traffic. Indeed, the current rule of the NHDS radio is that voice transmission always gets the first priority, and thus any data transmissions are cut off by voice transmission. This is because voice transmission is assumed to be a means of sending an emergency message. Thus, it may not be possible to send vehicle health information via the NHDS radio.

1.3 Goals

The first goal is to create a RVD prototype system collecting some of the in-car data that may be useful to evaluate the health of a cruiser and transmit the information to a repair facility in simulation. This RVD prototype system is expected to be an automated system so that it would benefit police cruisers in many ways. The prototype system automatically notifies a police cruiser's malfunction to headquarters in simulation. The automated system would reduce the manual labor examining a vehicle's health.

The second goal is to create recommendations for transmitting the RVD data on the NHDS radio system. First, the research may show that the RVD data cannot be transmitted on the NHDS radio. There is a possibility that the NHDS radio utilizes so much of its capacity that vehicle health data could not be sent via the radio often enough to be useful. If this is the case, then other wireless communication should be recommended to transmit the RVD data. On the other hand, the research may show that the NHDS radio has enough bandwidth for the RVD data transmission. If the current capacity of the radio can accept the RVD data, the recommendation should be the specific transmission time of the RVD data. The recommendation could show us when we can send the RVD data via the NHDS radio so that we minimize the interruption by other NHDS radio traffic.

1.4 Approach

The RVD prototype system requires six steps (Figure 1.3). The first step is to use an On-Board Diagnostics II (OBD-II) in-car network to collect vehicle data about the health of the vehicle. To connect the OBD-II network with the Project54 system, the OBD-II scan interface should be implemented. The OBD-II interface should be cost effective to be implemented in all the police cruisers. The protocol of the OBD-II interface should be easily programmable and compatible in the Project54 system so that no extra hardware is required.

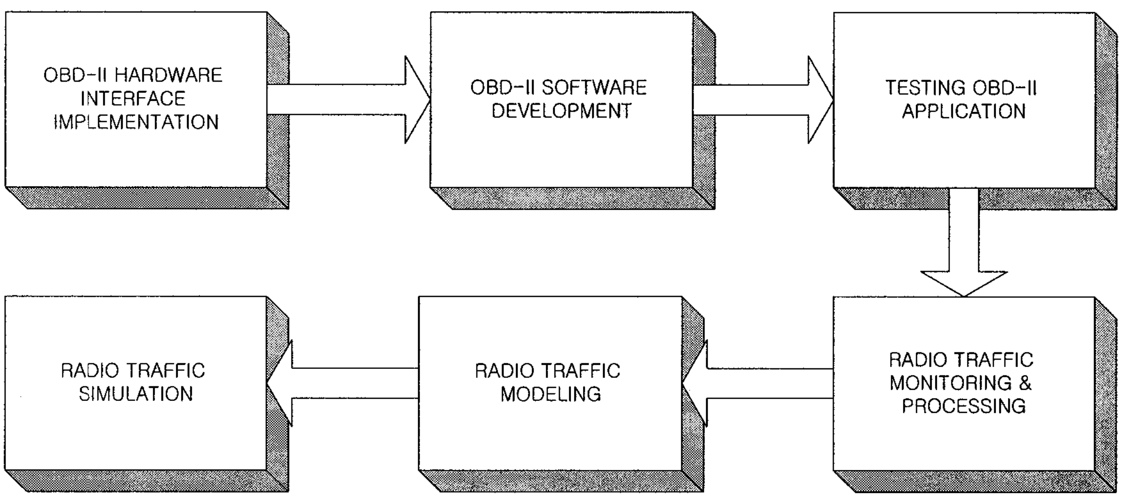


Figure 1.3 Six Steps for the RVD prototype implementation

The second step is the development of a Project54 software module to obtain the data and process the data from the OBD-II network. The software module should display the vehicle data in a clear manner to a police officer. The processed data supports the law enforcement fleet notifying the headquarters about the car accident, scheduling maintenance, and diagnosing a malfunction of a vehicle. Any malfunction of a vehicle will be displayed with a short description to a police officer and will be sent to the server via a telecommunication tool. Mileage information from the OBD-II network may be obtained to schedule maintaining a fleet of police cruisers. Data logging may be a useful tool in diagnosing a malfunction of a vehicle.

The third step is testing the software module. For this purpose, an OBD-II simulation tool should be built so that the algorithm can be easily tested in the laboratory environment. Once the prototype of the RVD application is fully tested in the laboratory, the confirmation can be done in the field.

Once the RVD in-car application with the three steps is completed, the fourth step is monitoring the current police radio traffic. Both voice and data transmissions will be monitored. Once the radio traffic is monitored, data processing is required to interpret simple recorded radio messages into mathematical data which can be understood in MATLAB.

The fifth step is to model the NHDS radio traffic. A few data modeling methods are suggested: channel utilization, cyclic time pattern recognition, and statistical distribution realization. Channel utilization is the time when the radio channel is occupied by either voice or data transmission per the total active time of the radio. Channel utilization is an indicator showing the current usage of the radio channel. This information gives a critical recommendation whether any transmission can fit in the current NHDS radio.

Cyclic time pattern may be recognized so that the timing of the RVD data transmission can be decided by the pattern. For instance, three o'clock in the morning may be the quiet time while four o'clock in the evening is the busy time for the radio traffic. If there is a clear evidence to show a cyclic time pattern, the recommendation can be the specific timing to transmit the RVD data without losing them. The cyclic time pattern can be recognized by a Fourier analysis or autocorrelation. However, the constraints of the recognition of the cyclic time pattern are the sampling theorem. For example, to recognize a one hour cyclic time pattern in the radio usage, a sampling period should be less than half an hour.

Statistical distribution of the radio traffic may be empirically realized and mathematically regenerated to simulate the radio traffic. The statistical distribution of the radio traffic indicates the statistics of how long a police officer uses the radio each time. The normalized empirical statistical distribution is compared with the mathematical statistical distributions which are chosen from an educated hypothesis. This radio traffic modeling process may be useful to regenerate the statistical distribution of the radio traffic without monitoring the radio traffic.

In the last step, a simulation is performed with the real radio traffic data and the RVD and GPS data. Depending on different scenarios of the RVD and GPS data transmission methods, the different simulation environment will be created. For instance, the RVD data can be transmitted every one minute or two minutes and so on. If these are the scenarios, then the simulations for each case can be performed and the result of each case can be compared to give a recommendation of the RVD and GPS transmission method.

In summary, six steps are suggested to build a RVD prototype for a law enforcement fleet. The first step is to implement the appropriate OBD-II interface in the

Project54 system. The second step is to develop the software to process the OBD-II data that may assist a law enforcement fleet manager. The third step is to test all the algorithms in the OBD-II software. Once the prototype of the in-car application is completed, the fourth step is to monitor and process the NHDS radio traffic. The fifth step is to model the radio traffic and the last step is to simulate the current radio traffic and the RVD data based on the model of the radio traffic.

CHAPTER 2

BACKGROUND

2.1 Vehicle Electronics

The vehicle industry has been developing in-car electronics systems since the electronic ignition was introduced in the early 1970s. Improving passenger's safety, vehicle efficiency, and the entertainment of passengers were the basic ideas for manufacturers to implement more sophisticated electronic means to attract their potential customers in a competitive market [3]. However, manufacturers had no concern with environmental protection in early stages of in-car electronics systems. An air pollution issue was raised in California, where the state government attempted to regulate the vehicle emissions by an on-board electronic control, which requires standardization in the vehicle industry.

2.2 OBD

The standard of the in-car electronic systems had not been established until 1985 when the Society of Automotive Engineers (SAE) initiated the standard and named it On-Board Diagnostics (OBD). This standard was revised by the Environmental Protection Agency (EPA) and the regulation was first applied to newer cars and light trucks in the State of California in 1988 [4]. The regulation states that the OBD system monitors the vehicle parts pertaining to emissions for their appropriate operation and if the functionality of the parts is not working properly, the OBD system illuminates a Malfunction Indicator Lamp (MIL) on the dashboard. The OBD system also stores the malfunction information of the vehicle parts to allow the technician to find out what has been causing the problems, simply by plugging a scan tool into the interface under the dashboard.

Even though the first generation of the OBD system provides some emissions related information, some inspection technology could not be implemented in the OBD system due to the technical constraints at that time.

2.3 OBD-II

All cars built in the U.S. since 1996 have the OBD-II system by federal regulation. OBD-II, the second generation OBD system, is a standard in the U.S. by SAE. The electronic signal, data format, and scan tool interface are all standardized to access the vehicle information for state inspectors [4].

Because technology had advanced for a few years after the first OBD system, OBD-II has more functionality which monitors such critical emissions related information as catalyst efficiency, engine misfire, and canister purge system. The technicians do not only examine emissions related malfunction by EPA regulation, but also non-environment-related malfunction of the vehicle.

Besides the regulated OBD-II protocol, each manufacturer keeps their non-emission related vehicle information such as fuel level, and vehicle voltage power where it can be obtained with a special procedure from OBD-II interface.

2.4 OBD-III

An OBD-III concept is being discussed in California [5]. The main idea of the OBD-III system is the utilization of wireless communication to minimize the delay between the detection of the emissions malfunction by the OBD system and the repair of the vehicle. The OBD information can be shared with the vehicle owner and the regulator such as patrol officers and private contractors.

This inclusion of the wireless communication on the OBD-II system raises several issues. First, a Federal Communications Commission (FCC) license is required to establish the connection between the various users, but wireless roadside communication bandwidth is already almost taken by commercial operators, law enforcement, and jurisdiction state agencies, etc. Second, each vehicle owner's private information should be treated carefully. Enormous vehicle information will be transmitted by air and shared with anyone and government. These issues have not been settled to be applied in reality even though wireless communication is ready to be implemented in the OBD system. However, the concept of the OBD system that involves the advanced communication has been researched and applied in commercial areas. The next section introduces the ideas of aftermarket remote diagnostics for vehicles.

2.5 Remote Vehicle Diagnostics Research

Remote diagnostics research has been conducted in many fields: building and factory maintenance, computer maintenance, network monitoring, and so on. The main benefits of remote diagnostics are saving travel costs, improving service efficiency and customer relations, and aiding in expanding manufacturing facilities both nationally and internationally [6]. Remote diagnostics research is also applied in the automobile industry so that manufacturers and customers can take advantage of these benefits.

One of the RVD studies is a collaborative research between IT University of Goteborg and Volvo in Sweden. Karimi et al at the IT University of Goteborg designed an RVD system for commercial vehicles [3]. The study investigates the software architecture which is practical, flexible, and cost effective based on Internet and wireless communication. A prototype is built to validate their RVD software architecture.

Azimzadeh at the IT University of Goteborg also conducted research on diagnosing the vehicle when the vehicle is moving [7]. He suggests that a technician can collect real time vehicle data when the vehicle is moving and allows the technician to become a remote worker diagnosing the vehicle via the Internet. In this case, the vehicle can be on the highway instead of being in the service center area where vehicle malfunctions may not be detected.

Klausner et al from the Robert Bosch Corporation studied RVD, and focused on the detailed description of the RVD in-car applications such as lifetime estimation and predictive diagnosis by vehicle data management system [8]. They suggest that we can estimate the technical lifetime of a vehicle system with the periodic log, tracking down the complexity of vehicle performance. This vehicle data management can prevent a vehicle from degradation and fatigue. It could also distinguish different types of faults by data analysis.

2.6 Public Safety Radio Analysis

Sprinkle, at Virginia Polytechnic Institute and State University, discussed many considerations such as trunked channel allocation, coverage, cost, and security for a design in a modern land mobile radio system in his master's thesis [9]. Sprinkle describes Project 25 (P25) adopted in the VHF high-band digital radio system. P25 is a standard developed by the Association of Public-Safety Communication Officials (APCO) providing interoperable radio solutions from different manufacturers. P25 also introduces Digital Signaling Processing (DSP). The DSP technique enables clear voice transmission and reliable digital data transmission.

Sharp et al modeled and analyzed the public safety radio traffic at Simon Fraser University [10]. They defined the characteristics of the radio traffic with call holding time and inter-arrival time and in order to understand the radio traffic, a few techniques are used to model the radio traffic such as autocorrelation, comparison of empirical distribution to theoretical distributions, and a lag plot. The result indicates that the inter-arrival times are exponentially distributed and correlated. The call holding times have a lognormal distribution and exhibit no correlation structure.

Song and Trajkovic modeled and simulated the public safety wireless network in Simon Fraser University [11]. They used the power spectrum analysis to find a cyclic time pattern. They found that daily and weekly patterns exist in the public safety wireless network. The research also introduced the simulation of call blocking probability and channel utilization. The statistical result simply showed that the more channels are available, the less calls are blocked. Channel utilization also decreases as the number of channels increases.

Aschenbruck et al measured and analyzed the public safety radio traffic in a disaster area scenario at University of Bonn in Germany [12]. In the scenario of the train accident in Germany, he measured the multiple channels of the public safety radio and analyzed the radio traffic with respect to the individual calls and conversation. He found that the distributions of both individual calls and conversation are lognormal distributions.

2.7 Other Network Traffic Analysis

Staehle et al at University of Wurzburg provides practical traffic model for mobile users in Germany [13]. Based on the assumption that the behavior of the wired communication traffic is the same as that of the wireless communication, the WWW traffic of the mobile networks is modeled in combination of many existing methods with respect to HTTP, Email, and FTP. The combination of the multiple models is accurate enough to be used in simulation studies for network planning purposes.

Farber at University of Stuttgart assesses both the server and client traffic models regarding a fast action multiplayer online game [14]. Two characters are considered in this study: inter-arrival time and packet size. Extreme value distribution is found to fit the best for both the inter-arrival time and packet size in the modeling of the server. Meanwhile, deterministic distribution is suggested for inter-arrival time in the modeling of the client and extreme value distribution is suggested to fit for the packet size.

However, shifted lognormal or shifted Weibull distribution are acceptable fits instead of extreme value distribution.

Xhafa and Tonguz evaluate the impact of mixed lognormal distribution of channel holding time on the handover performance in cellular networks [15]. The Monte-Carlo simulation technique is used to prove their hypothesis. The handover performance with the exponential distribution is assessed via the real network data analysis. Meanwhile, the performance with the mixed lognormal distribution is evaluated via the Monte-Carlo simulation. The simulation result shows that there is no difference of handover performance between exponential and mixed lognormal distributions.

CHAPTER 3
PROTOTYPE IN-CAR REMOTE VEHICLE DIAGNOSTICS APPLICATION

The first three proposed steps of this research were creating a prototype in-car RVD application in the Project54 system. The prototype RVD in-car application is one of the distributed components in the RVD system [3]. The application is named OBD-II Scan Application since it interacts with the OBD-II network. There are three main tasks of the OBD-II Scan Application. First, the OBD-II Scan Application communicates with the OBD-II network. The OBD-II Scan Application requests the vehicle data from the OBD-II network. Once the OBD-II network responds, it displays the data and stores the vehicle data in the daily based file. Second, the OBD-II Scan Application can send vehicle information via the Proxy Application [16], which is the proxy handling any messages via a telecommunication tool, in the case of the vehicle data update or emergency notification. Third, the OBD-II Application processes vehicle information: mileage estimation, speed alert, and vehicle power voltage display.

This chapter describes the RVD in-car application. Section 3.1 describes the OBD-II hardware interface implementation on the Project54 system. Section 3.2 details the OBD-II software development: a brief description of the OBD-II protocol, a basic functionality of the OBD-II software displaying and storing the vehicle data, the implementation of the Diagnostics Trouble Code (DTC) notification, vehicle power voltage display, speed alert, and mileage estimation. Section 3.3 shows the testing procedure of the OBD-II Scan Application with a simulation tool.

3.1 OBD-II Hardware Implementation

The first proposed step of this research was connecting the OBD-II network with the Project54 system. Before implementing the OBD-II interface into the Project54 system, we need to understand the various OBD-II electrical signals. There are five different OBD-II electrical signals in use, each with minor variations in the communication pattern between the on-board diagnostic computer and the scanner console or tool.

The five different OBD-II electrical signals can be distinguished by which pins is used on the J1962 connector, the OBD-II connector (Figure 3.1). Society of Automotive Engineers (SAE) J1850 PWM (Pulse Width Modulation) is used in pin 2 and pin 10. The Ford Motor vehicles use PWM. SAE J1850 VPW (Variable Pulse Width) is used in pin 2. The General Motors vehicles use VPW. International Organization for Standardization (ISO) 9141 and ISO 14230 KWP2000 are used in pin 7 and pin 15. The Chrysler, European, and Asian vehicles use ISO 9141 and ISO 14230 KWP2000. ISO 15765 CAN is used in pin 6 and pin 14. In fact, ISO 15765 CAN will substitute all the other OBD-II electrical signals by 2008. Even though there are five different OBD-II electrical connection protocols, the diagnostic message formats for all OBD-II compliant vehicles are identical and the message format is hexadecimal.

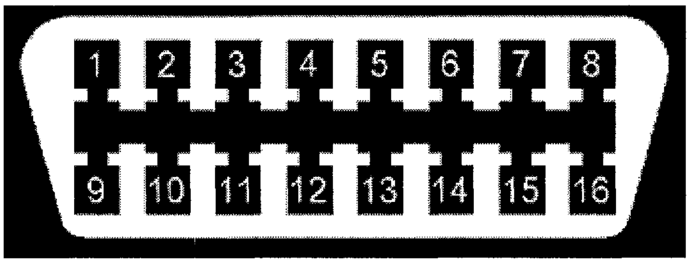


Figure 3.1 J1962 Connector

In this research, we used an off-the-shelf OBD-II interface [17] (Figure 3.2). This interface was the ELM320 by ELM Electronics since the ELM320 is a RS-232 connection compatible tool. No extra hardware is required to connect it to the Project54 IDB network. The format of the ELM320 communications is the ASCII characters and the command set is 'AT' command set, which is a conventional command set. The conventional command set is easy to understand to program the interface. Also, the ELM320 is a cost-effective design (it cost under $20) that can be deployed in thousands of police cruisers.

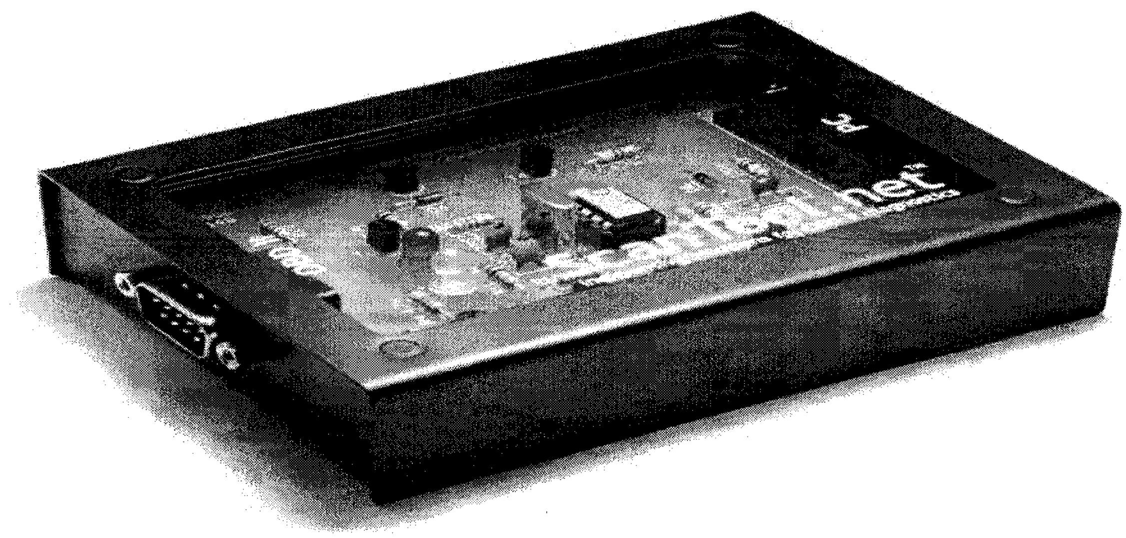


Figure 3.2 ELM320, OBD-II interface [17]

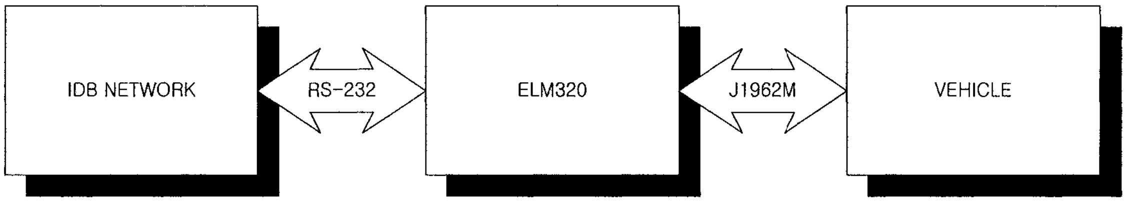


Figure 3.3 ELM OBD-II interface between the car and the IDB network

In this research, we worked with a Ford Crown Victoria 2003 police cruisers. The J1962M interface is connected to the OBD-II port under the dashboard in Ford Crown Victoria 2003 police cruisers. Once the ELM320 is connected to the OBD-II port, it is powered by the OBD-II network. The RS-232 protocol is used to connect between ELM320 and the IDB network (Figure 3.3).

3.2 OBD-II Software Development

The second proposed step of this research was developing a Project54 software module to obtain, process, and send the vehicle data via a telecommunication tool. For the development of the software module, the OBD-II standard message format is learned first. Based on the knowledge of the OBD-II standard message format, the Project54 software module processes and send the vehicle data in simulation.

3.2.1 General Information about the OBD-II Message Format

After the OBD-II interface hardware implementation on the Project54 system, there is need to understand the OBD-II message format to obtain the vehicle data from it. There are different types of vehicle information to be gained from OBD-II. In Project54 we utilize three different modes: Mode 01, Mode 03, and Mode 22. Mode 01 is called the

Diagnostic Test Mode described in detail by the SAE J1979 (APR2002). Mode 03 is called the Diagnostic Trouble Code (DTC) described in detail by the SAE J2012 (APR2002). Mode 22 is a mode to request the Ford Enhanced Parameter Identification (PID). It is described by the SAE J2190 briefly, but not in detail since this mode requests the non-standard OBD-II parameters which is Ford proprietary information. Mode 22 does not necessarily meet the requirements from the EPA. However, it contains such critical parameters as fuel level and vehicle power voltage for the RVD system.

3.2.2 Vehicle Data Display and Log

Vehicle data can be accessed through the OBD-II interface. This section describes how we obtain vehicle data in succession with Mode 01 and Mode 22. The purpose of Mode 01 is to allow access to current emission-related data values, including analogue inputs and outputs, and system status information. The request for information includes PID values that indicate to the on-board system what specific information was requested. For instance, in the message format "01 0C", "01" indicates Mode 01 and "0C" indicates the PID, which requests engine Revolution per Minute (RPM). The vehicle's Electronic Control Unit (ECU) responds with "41 0C 0F 00." In the message, "41" indicates that is the response to Mode 01, "0C" shows the requested PID, and "0F 00" is an actual RPM (9600 RPM in this example). In this thesis, using Mode 01 we request vehicle speed, engine RPM, engine load value, and engine temperature (Figure 3.4)

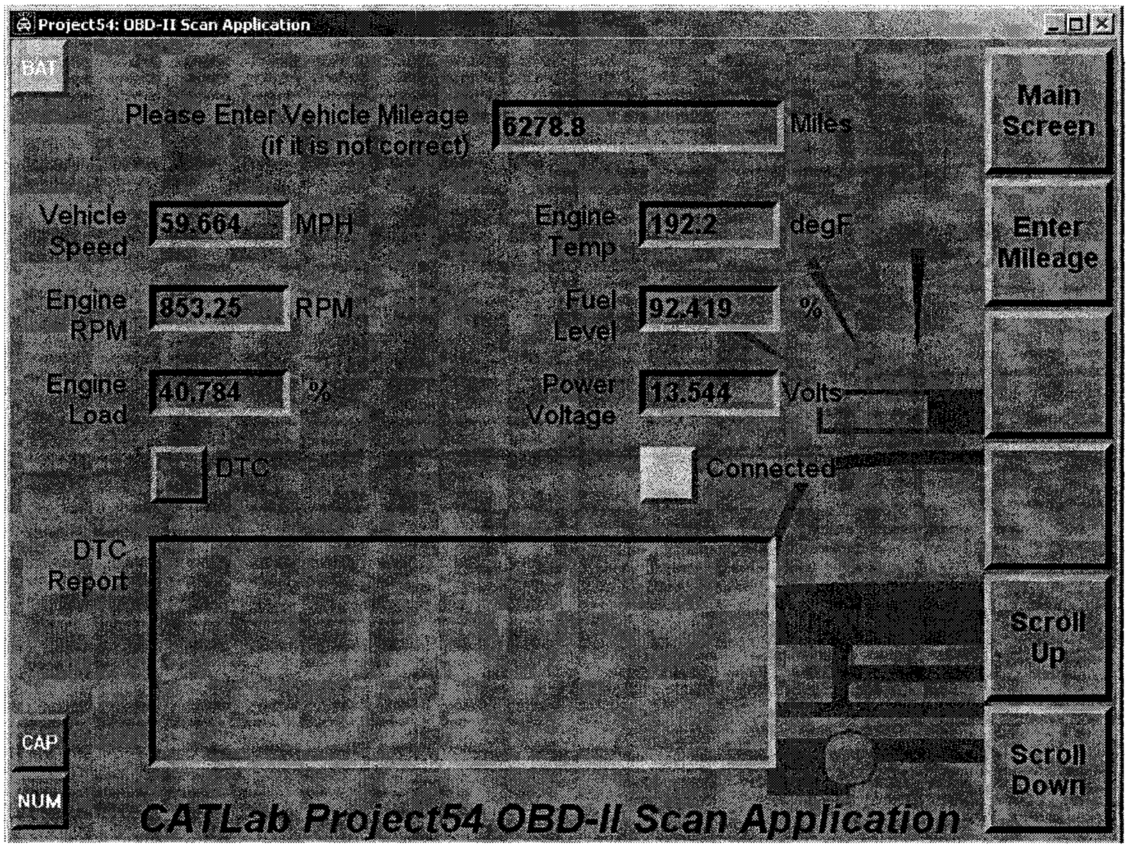


Figure 3.4 Mode 01 in Red Boxes

Mode 22 is the non-standard OBD-II protocol providing various vehicle data which are not necessarily required by the EPA. This non-standard OBD-II protocol for Ford cars is used to obtain such critical vehicle information as fuel level and vehicle battery voltage power measurement. Fuel level and battery voltage information is readable from the OBD-II interface, but mileage was not (Figure 3.5).

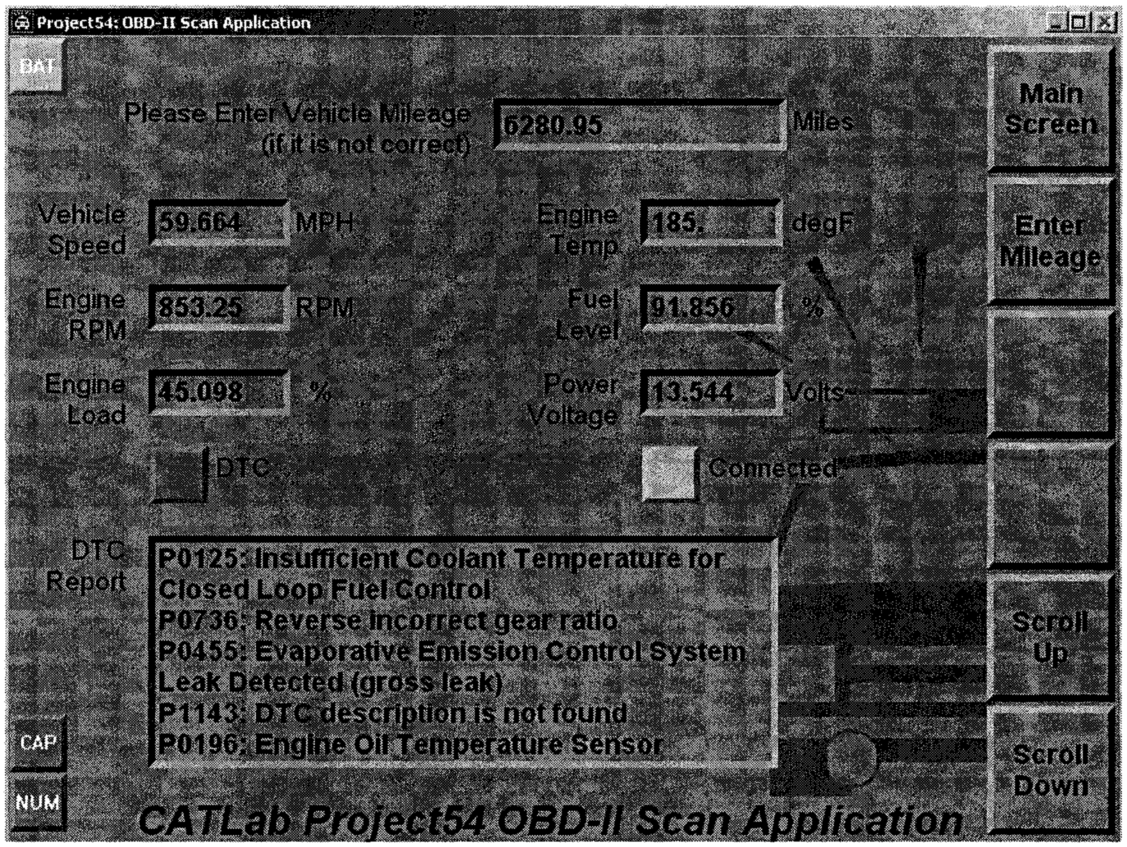


Figure 3.5 Mode 22 in Red Box

After the OBD-II Scan Application reads the vehicle data, it saves the data in the daily based file. When a police officer logs on the database in the Project54 server, the OBD-II Scan Application sends the vehicle data via a telecommunication tool.

The flow chart describes the vehicle data acquisition, display, and log of the OBD-II Scan Application (Figure 3.6). The total cycle takes about 26 seconds depending on the speed of the data acquisition.

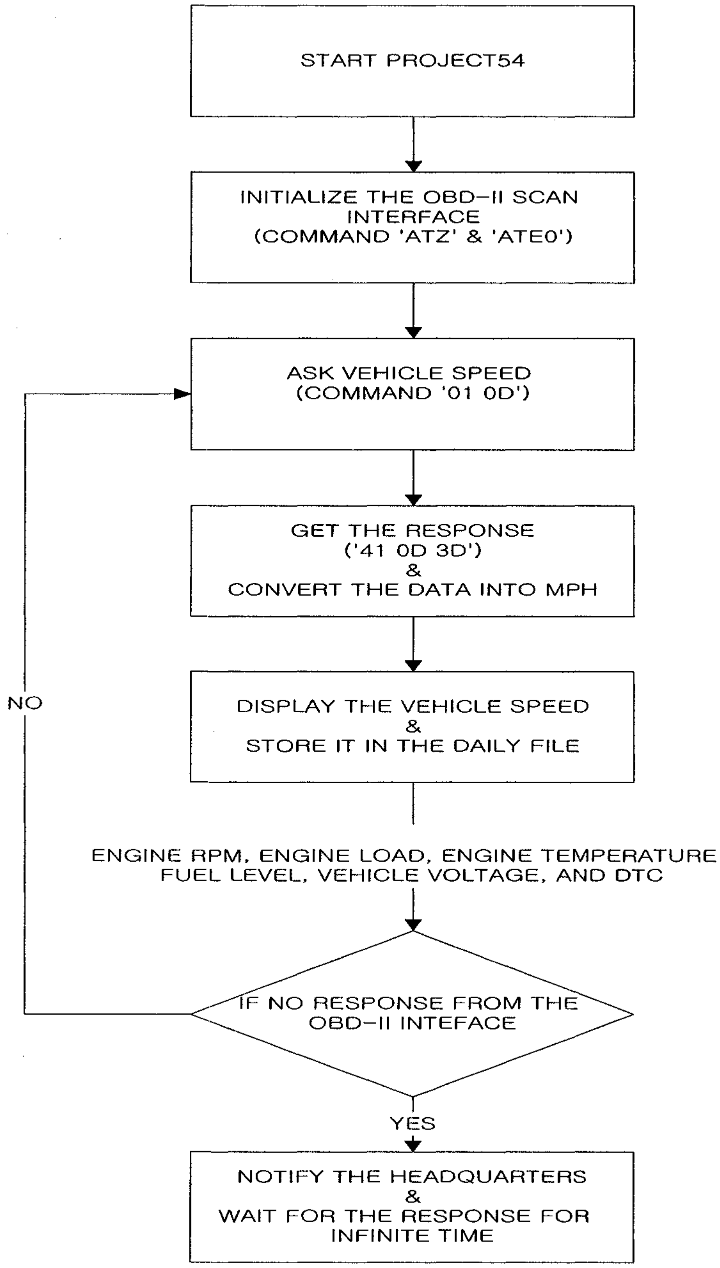


Figure 3.6 Flow Chart of OBD-II Application

3.2.3 Diagnostics Trouble Code (DTC) Alert

The purpose of 'DTC Alert' is to enable the fleet manager to obtain the reports of the confirmed emission-related malfunctions. Any message describing vehicle malfunction through the OBD-II interface is called Diagnostics Trouble Code (DTC). The procedure to obtain the DTCs is described next.

There is a two step process for the external test equipment to obtain DTCs. The first step is to send Mode 01 command "01 01" to request the number of emission-related DTCs from all ECUs that have vehicle malfunction information available. Each ECU that has one or more DTC(s) stored responds with a message that includes the number of stored DTC codes to be reported. If an ECU is capable of storing emission-related DTCs and does not have stored DTCs at that time, then the ECU responds with a message indicating that no DTCs are stored.

The second step is to send Mode 03 command "03" to request all emission-related DTCs. Each ECU that has DTCs available responds with one or more messages, each containing up to three DTCs. Each DTC is transmitted in two bytes of information. The first nibble indicates whether the code is for a set of Powertrain, Chassis, Body, or Network DTC. The second nibble and the second byte indicate the actual DTC. For example, "02 98" would be displayed to technicians as P0298 indicating a Powertrain DTC of 298. It indicates that the Engine Temperature Protection strategy in the Power Control Module (PCM) has been activated. This will temporarily prohibit high speed operation by disabling injectors, therefore reducing the risk of engine damage from high engine oil temperature. If no emission-related DTCs are stored in the ECU, then the ECU responds with a series of zeros to this request.

To build DTC alert functionality in the OBD-II Scan Application, DTC is requested every 26 seconds to detect any malfunction of vehicle operation in the OBD-II Scan Application. Once DTCs have been obtained, the Application displays the DTCs and the descriptions of each DTC (Figure 3.7). There is a separate DTC description file and if there is no description contained in the file, the OBD-II Scan Application displays the message, "DTC description is not found." Simultaneously, the OBD-II Scan Application sends the emergency notification called 'DTC Alert' that contains all DTC codes to the server via a telecommunication tool.

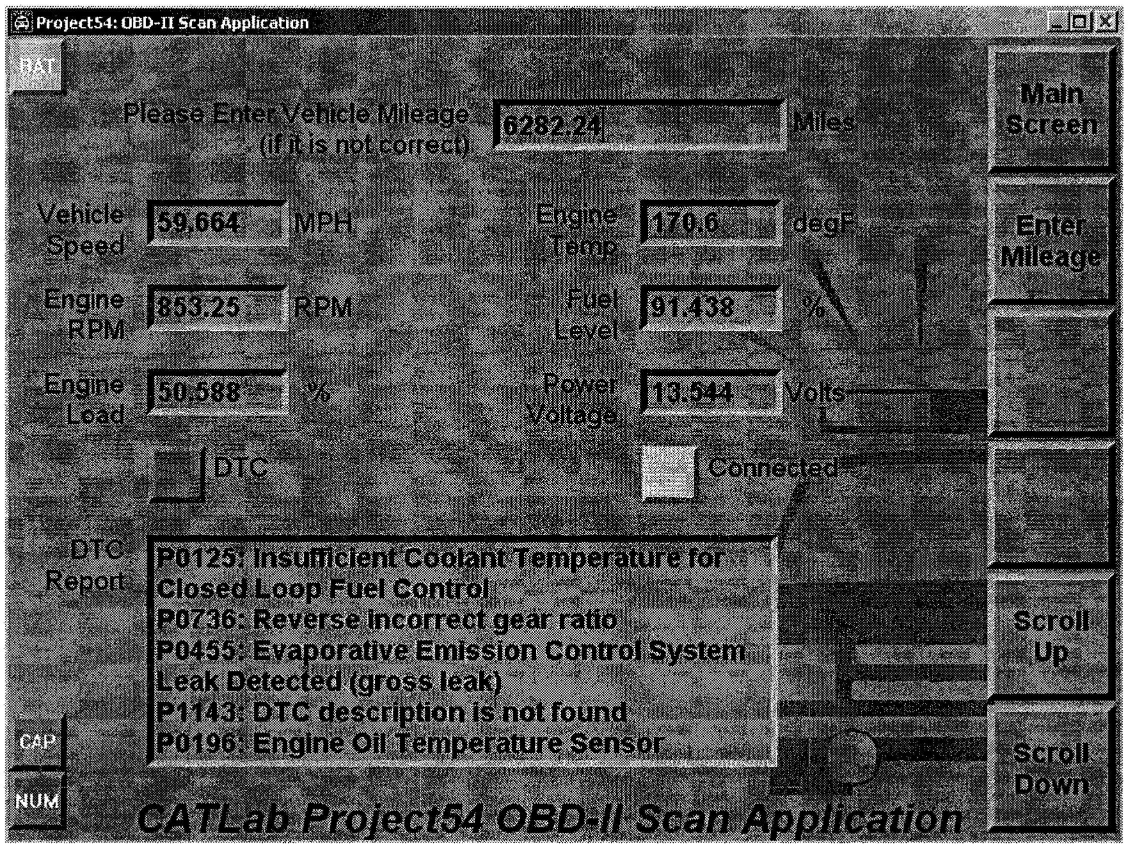


Figure 3.7 DTC Dispaly

Figure 3.8 is a flow chart describing the procedure of 'DTC Alert.' Once the DTCs are detected, the OBD-II Scan Application sends the DTC information to the server via a telecommunication tool immediately.

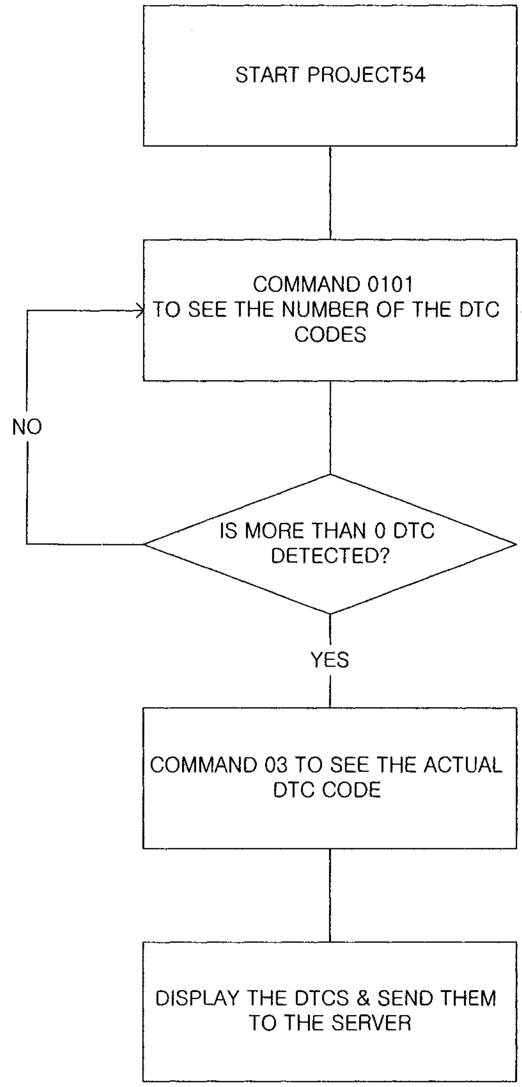


Figure 3.8 Flow Chart of DTC Acquisition

3.2.4 Vehicle Power Voltage Display

Police cruisers are heavily loaded with electrical equipment necessary for police work such as lights and siren, radar, GPS, radio, and so on. It is important to monitor the status of the vehicle battery for police cruisers because the police cruiser's equipment drains a lot of power from the vehicle battery. Moreover, the IDB network and the computer consume the vehicle battery. The drained battery might leave a police car vulnerable. To prevent this, the OBD-II Scan Application displays the vehicle battery voltage and stores the information.

The vehicle battery voltage is displayed with a colored square icon on the top left GUI on every Project54 Application. There are three different colors to represent the level of the vehicle voltage: green, yellow, and red (Figure 3.9). Green represents that the voltage is greater than 13 V. The normal status of vehicle voltage generated by the alternator is 13 V. Yellow represents that the voltage is greater than 10.5 V and less than 13 V. Red shows that the voltage is less than 10.5 V. The critical voltage point is defined to be 10.5 V by Ford 2000 Service Manual [18]. If the voltage is below 10.5V, the battery is discharged, or the alternator and the battery may be disconnected.

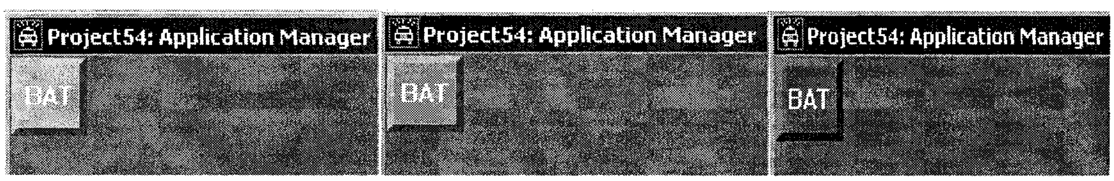


Figure 3.9 Vehicle Power Voltage Display

3.2.5 Speed Alert

Speed information can be critical to be reported right away to headquarters from police cruisers. In creating the application we envisioned the following demonstration scenario. If a cruiser exceeds the velocity of 100 miles/hour for more than 30 seconds, this means that the cruiser is pursuing a vehicle. If this is the case, headquarters should be notified. Therefore, the OBD-II Scan Application keeps track of the speeds it obtained (generated randomly in our test case) and looks for periods of 30 seconds or more during which the speed was consistently over 100 miles/hour. When a sequence like this is encountered the OBD-II Scan application sends a message to the server-side application.

For test purposes the speed alert algorithm in the OBD-II Scan Application sets the timer at five seconds instead of 30 seconds. Thus, if the vehicle speed exceeds 100 miles/hour more than five seconds, the OBD-II Scan Application sends a message to the server-side application via a telecommunication tool. The speed alert algorithm creates a random sequence of numbers between 80 and 117, representing the vehicle speed. A new number is generated approximately every second. Figure 3.10 shows a sequence of numbers generated over a period of about 30 seconds.

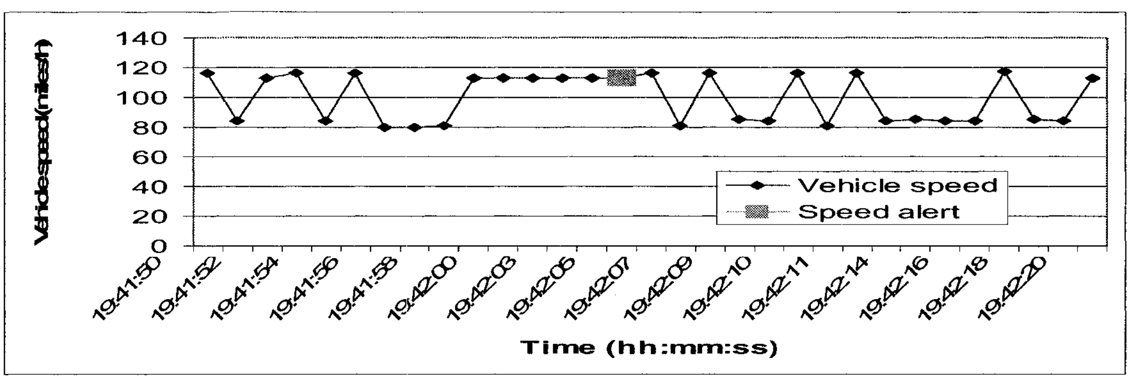


Figure 3.10 Simulated OBD-II vehicle speed readings

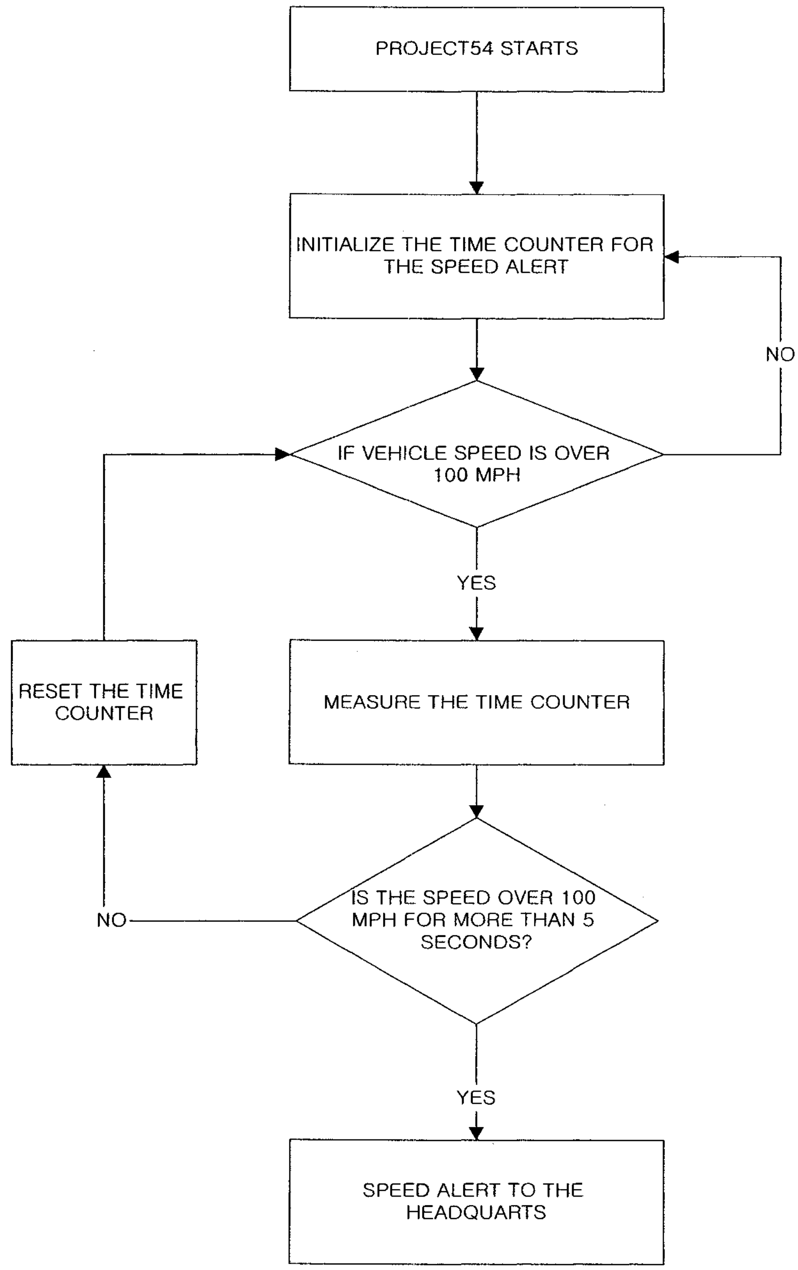


Figure 3.11 Flow Chart of Speed Alert

Figure 3.11 shows the flow chart of the Speed Alert. Once the time counter is initialized, the OBD-II Scan Application watches the vehicle speed. If the vehicle speed is over 100 MPH for more than five seconds, the OBD-II Scan Application sends "Speed Alert" message with the vehicle speed.

3.2.6 Mileage Estimation

Mileage of any vehicle is critical information to maintain the vehicle. Based on mileage, we change the oil, replace the parts of the vehicle, and furthermore estimate the lifetime of the vehicle.

Since mileage information is not the OBD-II standard parameter, vehicle mileage cannot be obtained from the OBD-II network. However, mileage is very important to maintain a fleet. Therefore, mileage is estimated based on vehicle speed and fuel level of a vehicle in the OBD-II Scan Application.

The calculated mileage information is always stored in the OBD-II Scan Application Registry key. When a police officer executes Project54, the OBD-II Scan Application loads the saved mileage information from the registry when the Project54 program is being turned off. Once the mileage information is loaded from the registry, the mileage estimation algorithm updates new mileage information based on the vehicle speed and stores the mileage information in the OBD-II Scan Application key.

However, the problem is that the OBD-II Scan Application can only obtain the mileage information when Project54 is on. When Project54 is off, the mileage information cannot be updated and therefore the number of miles driven will be missing. To minimize this problem, we use two back-ups to the mileage estimation method. The first back-up of the mileage estimation is that simply the mileage can be typed and stored in the registry any time by hand (Figure 3.12). Whenever police officer or manager found the fact that the mileage on the dashboard does not match with the mileage that appears on the OBD-II Scan Application, s/he can correct the vehicle mileage information by entering the mileage on the dashboard into the OBD-II Scan Application GUI. The vehicle mileage is displayed in the OBD-II Scan Application GUI.

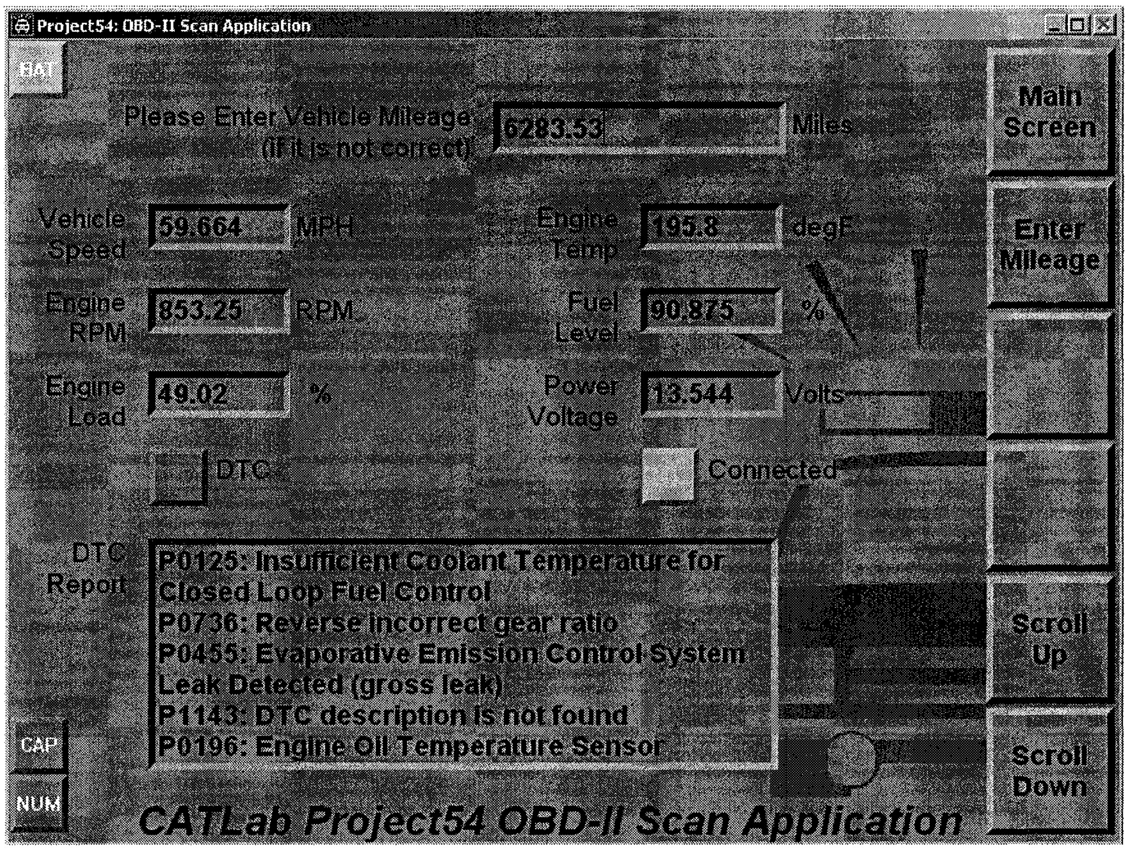


Figure 3.12 Mileage Entrance

The OBD-II Scan Application tries to keep up the mileage information automatically. Thus, the second back-up plays a role in the mileage estimation. The OBD-II Scan Application keeps an eye on the fuel level information as well as the vehicle speed for the mileage estimation. When the Project54 starts, the OBD-II Scan Application compares the current fuel level and the latest fuel level that is saved in the registry when the Project54 was being turned off. If the current fuel level is less than the old fuel level that is saved in the registry by the tolerance criterion, the mileage estimation algorithm adds up the missing mileage when the Project54 was turned off. Otherwise, the mileage estimation algorithm ignores the fuel level fact. The tolerance distinguishes the difference between the fuel consumption and the fluctuation of the fuel level (in our case, the tolerance criterion is 3% of the fuel level). The OBD-II Scan Application assumes that the car is driven a certain number of miles and adds the mileage that is missing when the Project54 is off. Figure 3.13 shows the flow chart of the mileage estimation algorithm.

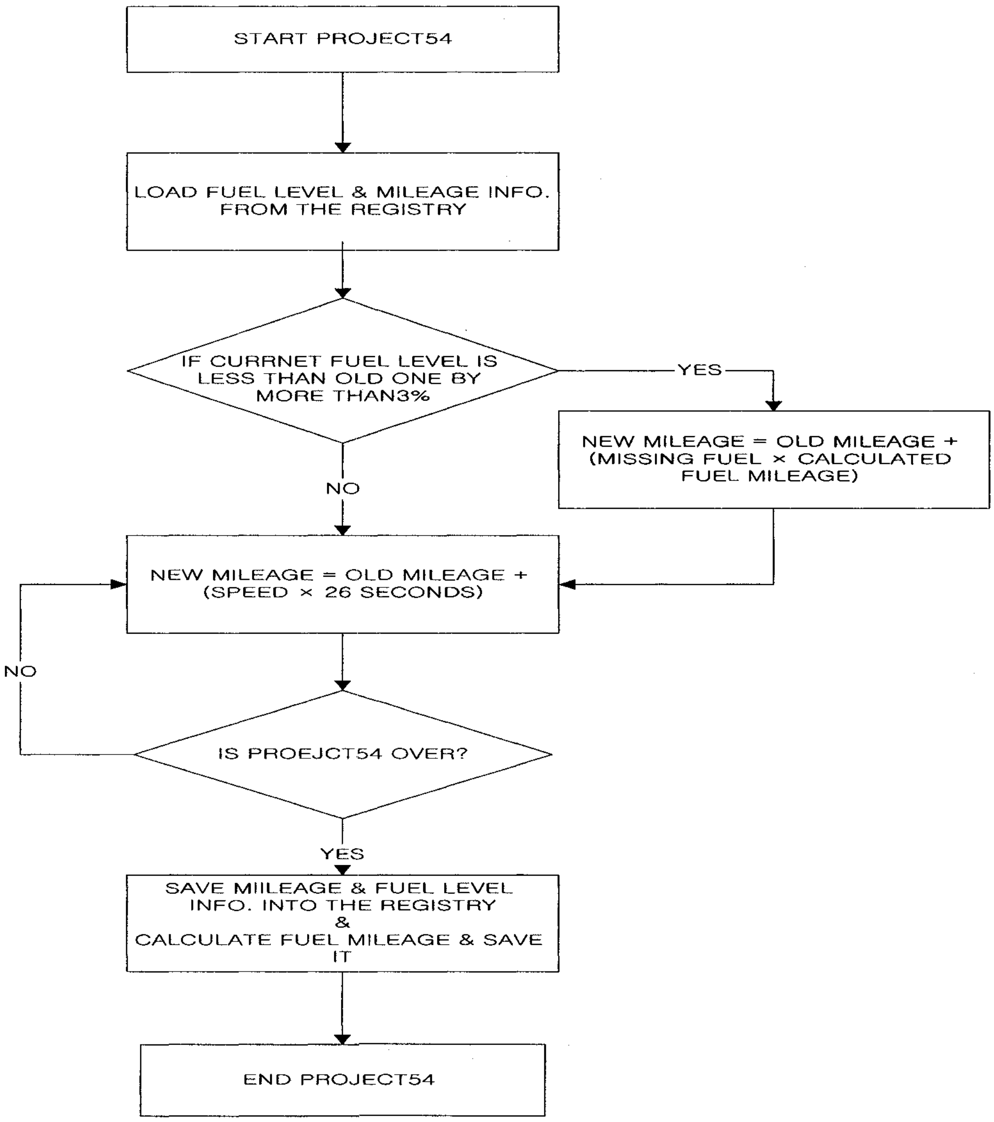


Figure 3.13 Mileage Estimation

This automatic mileage update by the fuel level meets one problem on progress. The problem turns out that the fuel level information from the OBD-II network of the car is raw data. The swing of the fuel level due to a characteristic of liquid is so radical that it is very rough to estimate the gas mileage information from the fuel level of the vehicle.

Figure 3.14 shows the fuel level data recorded on September, 9, 2005. There are high frequency components in the fuel level record. The maximum swing of recorded fuel level data is 21.5 % of fuel level so that it is hard to come up with the accurate gas mileage information.

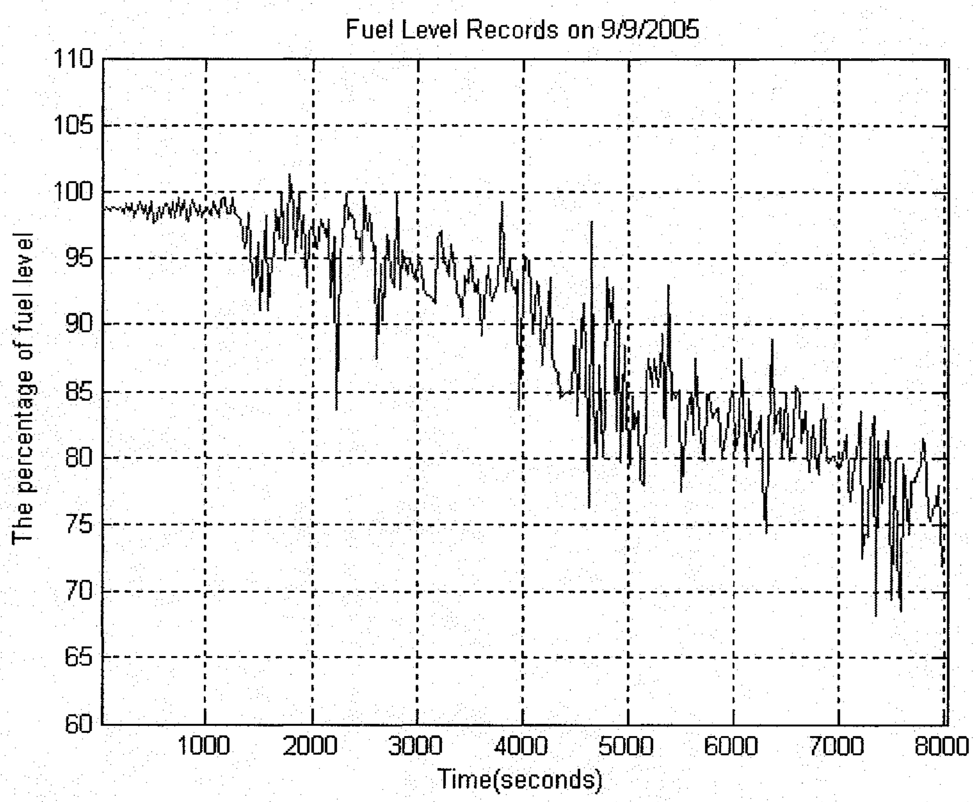


Figure 3.14 Fuel Level Records on 9/9/2005

Since the problem is the high frequency components of the fuel level reading, a FIR low pass filter is applied to reduce the high frequency components. The sampling frequency is 1/26 Hz and there are 309 sample points (Figure 3.14) and we perform Fast Fourier transform (FFT) on the fuel level data to see the frequency components in MATLAB (Figure 3.15).

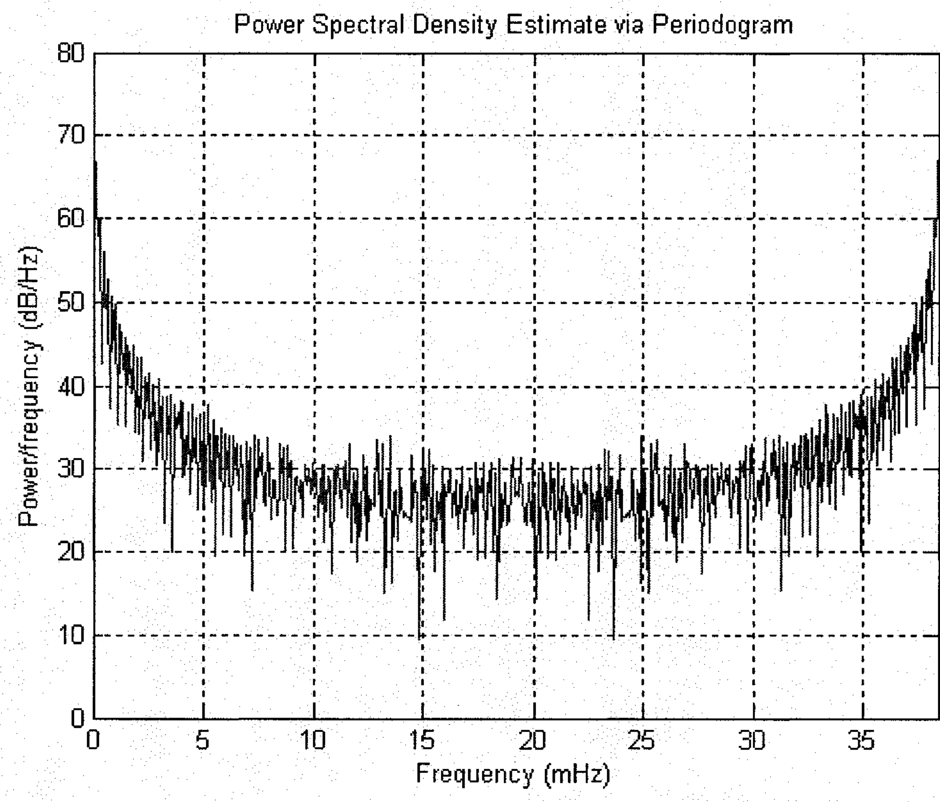


Figure 3.15 Periodogram on Fuel Level on 9/9/05

To cut off the high frequency components, the MATLAB FIR low pass filter function is used. The cut-off frequency is 1/5 of the half sampling frequency which is 1/52 Hz and there are 13 coefficients (Figure 3.16). Hence, components above 3.8 mHz frequency are cut off (Figure 3.17).

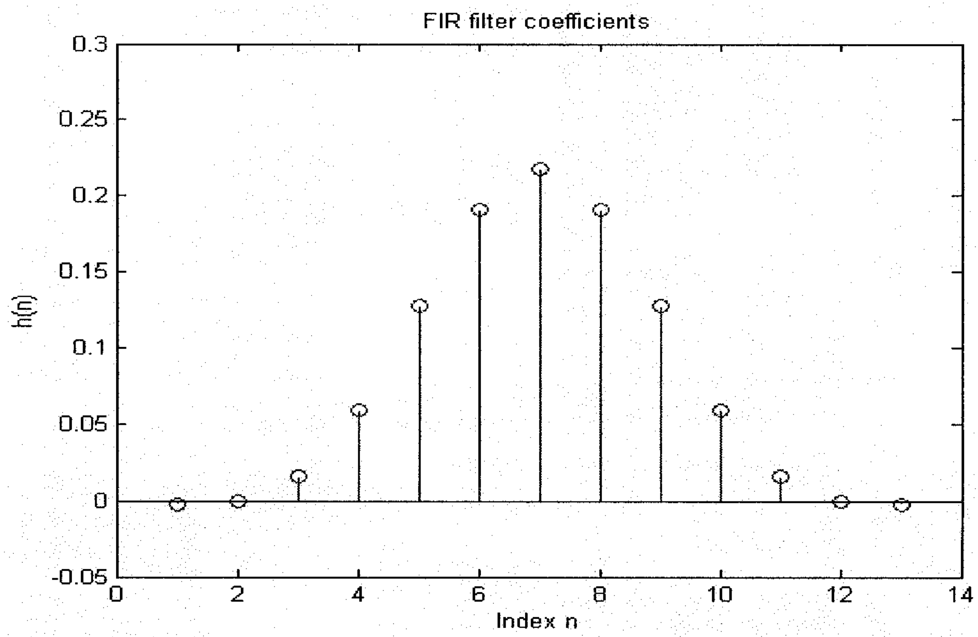


Figure 3.16 FIR Low Pass Filter Coefficients

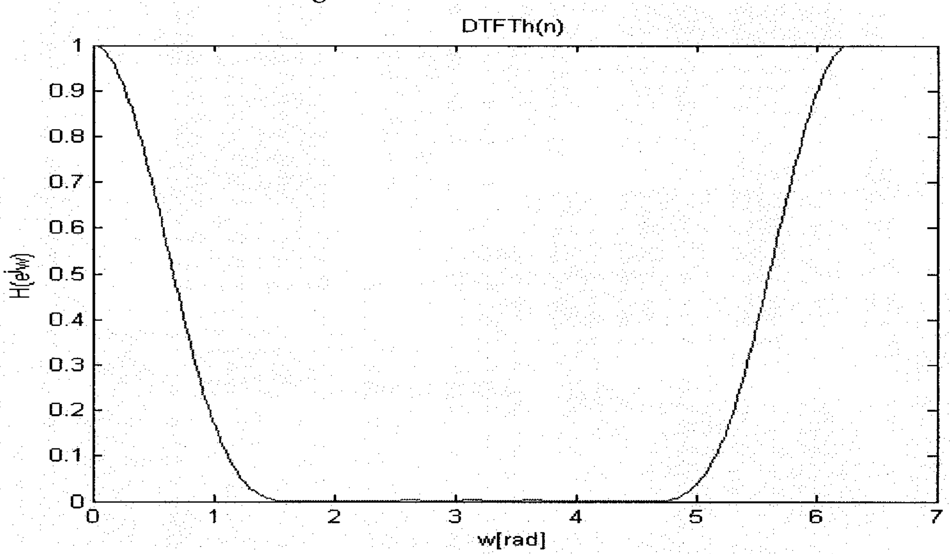


Figure 3.17 DTFT H(e^{jw})

The convolution of the fuel level data and the FIR low pass filter coefficients is performed to see the effect of the low pass filter (Figure 3.18). Since the coefficients are 13, the first 13 points in the convolution are way off from the original fuel level.

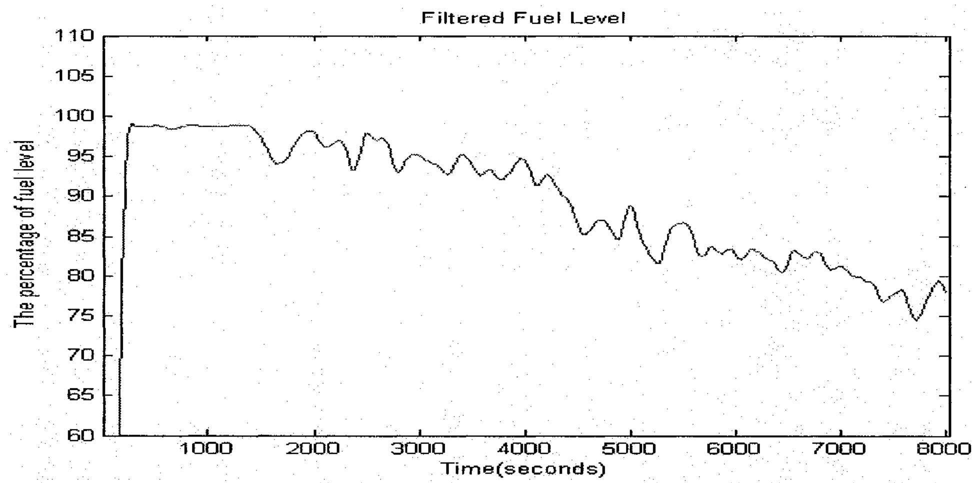


Figure 3.18 Filtered Fuel Level

Figure 3.19 shows the power spectrum of the fuel level recording after filtering. The magnitude of the high frequency components are dramatically reduced from average 30 dB to average -40 dB with the FIR low pass filter.

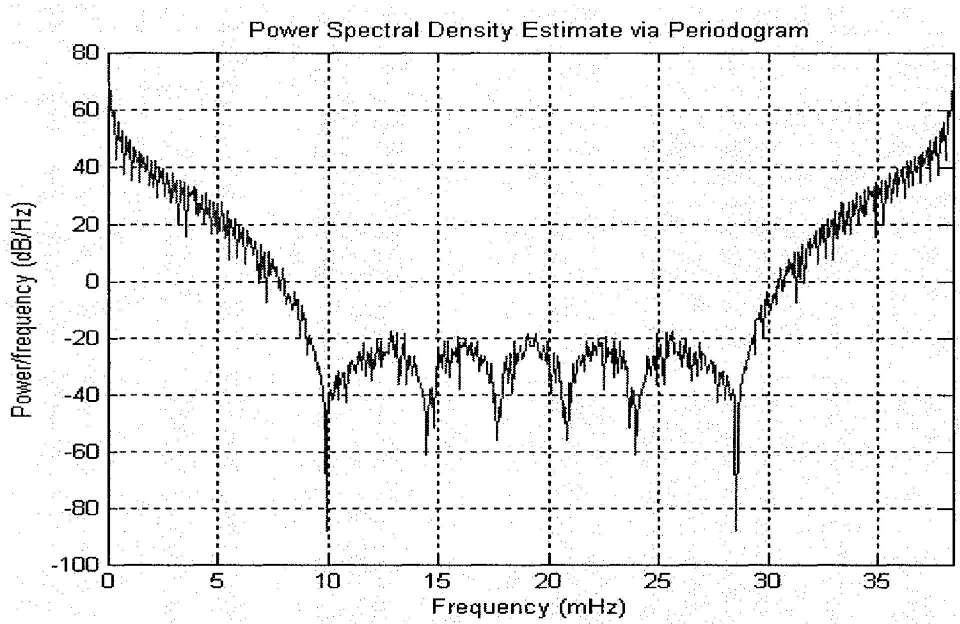


Figure 3.19 Power Spectral Density Estimate After Filtering

In the OBD-II Scan Application the first 13 fuel data is filled with the original data to solve the starting problem with the first 13 fuel data from the convolution (Figure 3.20).

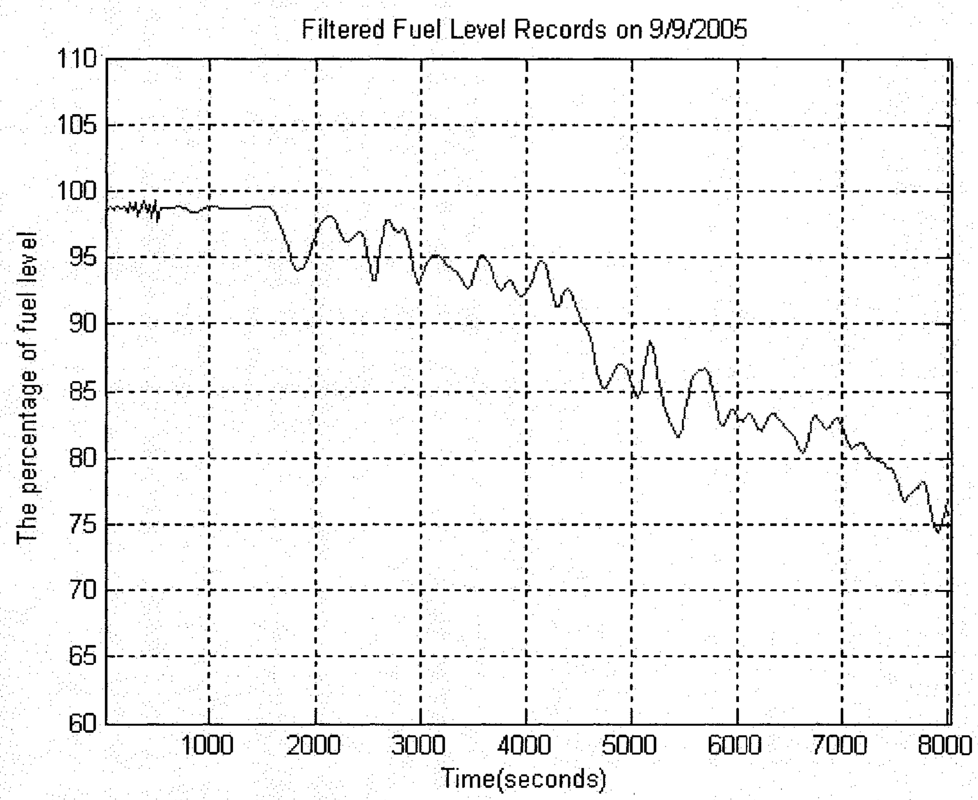


Figure 3.20 Filtered Fuel Level Records with 13 Initial Fuel Level Data

The filter of the fuel level performs well according to Figure 3.20. The fluctuation is reduced from maximum 21.5% to maximum 1.45 %. This FIR filter helps stabilizing the calculation of the gas mileage. In the next section, the test results from the simulation and the actual on-road test will be demonstrated.

3.3 Testing OBD-II Scan Application

The third proposed step of this research was testing the OBD-II Scan Application. The OBD-II Interface simulation tool is developed for the test of the OBD-II Scan Application. The OBD-II Interface simulation tool is called 'OBD-II Simulator' and it pretends to be the OBD-II network of the vehicle (Figure 3.21). We can either enter the vehicle data in the GUI or save the vehicle data in the 'OBD-II Simulator' folder so that it can manipulate vehicle speed, fuel level, fuel consumption rate. This simulator can test out a basic OBD-II data acquisition, speed alert functionality, mileage estimation algorithm, and fuel mileage estimation algorithm of the OBD-II Scan Application in the Project54 system.

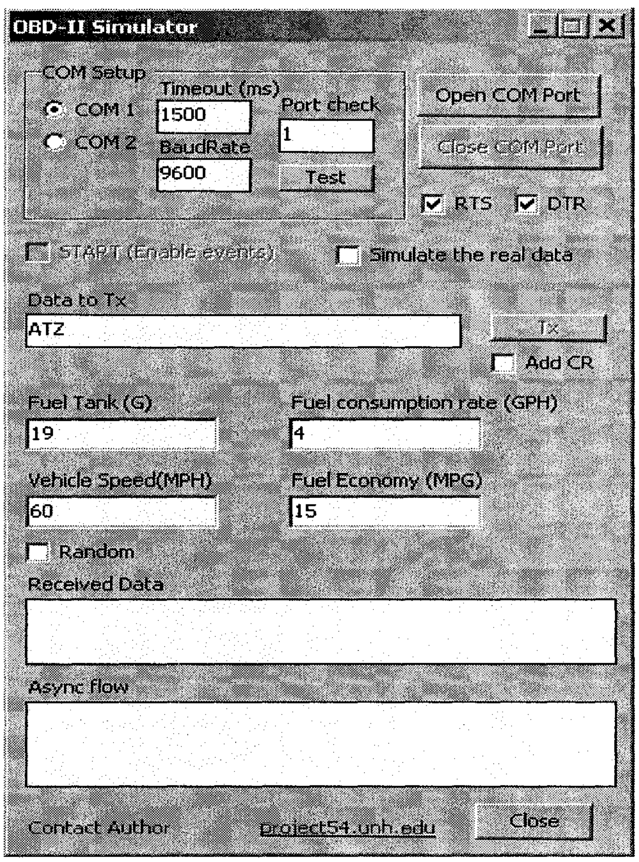


Figure 3.21 OBD-II Simulator

3.3.1 A basic OBD-II Data Acquisition Test

Fist of all, a basic OBD-II data acquisition in the OBD-II Scan Application is tested with the OBD-II Simulator. Figure 3.22 shows the test setup to confirm the data acquisition functionality of the OBD-II Scan Application. All the OBD-II data are stored in the correct order in this test (Table 3.1).

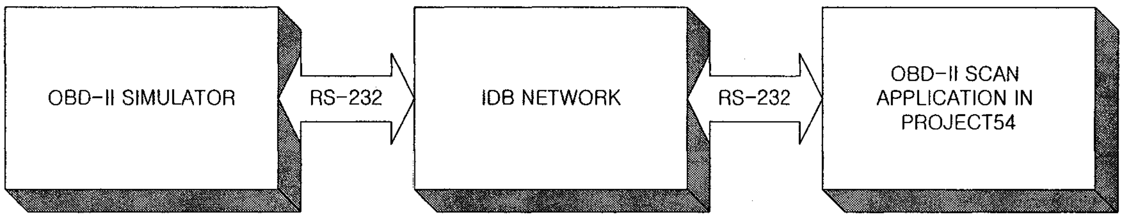


Figure 3.22 Test Setup for a basic OBD-II Data Acquisition

Time	Speed	RPM	Engine Load	Engine Temperature	Fuel Level	Vehicle Voltage	Mileage
14:01:45	62.772	853.25	49.02	188.6	92.648	13.75	26.39769
14:02:09	57.8	853.25	48.235	176	92.265	13.75	26.81514
14:02:34	57.8	853.25	50.196	143.6	92.088	13.75	27.23258
14:02:58	51.585	853.25	44.706	159.8	92.142	13.875	27.60514

Table 3.1 Tested OBD-II Data Recording

3.3.2 Speed Alert & DTC Alert Test

Speed Alert functionality is tested with the OBD-II Simulator. When the OBD-II Simulator constantly sends vehicle speed over 100 mph to the OBD-II Scan Application, the OBD-II Scan Application counts the time and if the speed of vehicle is more than 100 mph for more than 30 seconds, the OBD-II Scan Application sends 'Speed Alert' message with the actual vehicle speed to the OBD-II test server via the Ethernet connection.

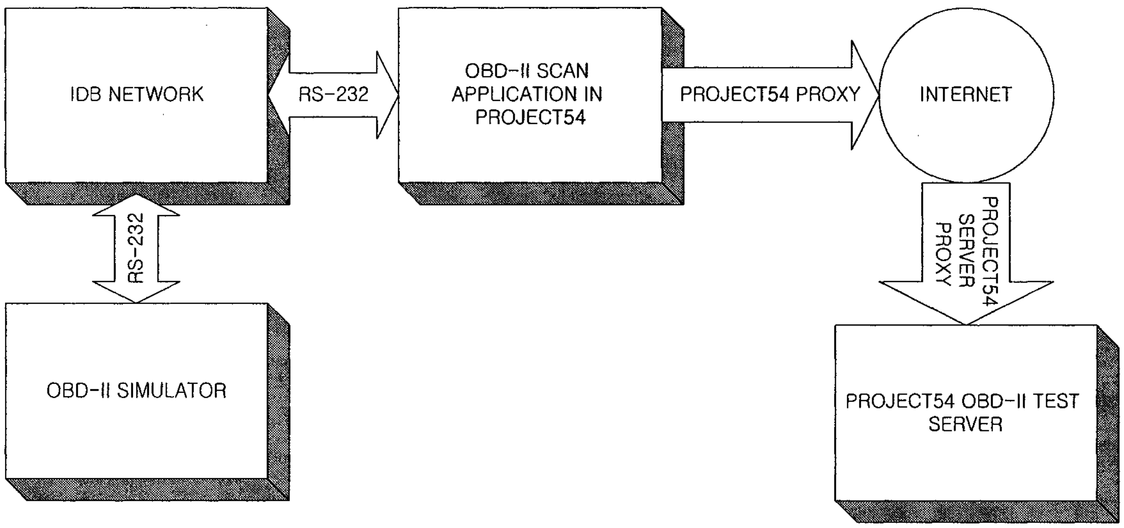


Figure 3.23 Speed Alert and DTC Alert Test Setup

Figure 3.23 shows the test setup for the speed alert. This test setup is similar with the test setup from our previous work [19]. The only difference is the addition of the OBD-II Simulator. The OBD-II Simulator is connected to the IDB network to perform the exact OBD-II in-car network. Once the OBD-II Scan Application interacts with the OBD-II Simulator, the OBD-II Scan Application collect, process, and send vehicle information to the OBD-II Test Server via the Ethernet connection. There are two proxies to handle the messages: Project54 Proxy and the Project54 Server Proxy. Each proxy handles the messages either for the Project54 in-car Applications, or for the Project Server Applications.

Recorded Time	Generated Speed
14:01:20	89.497
14:01:44	109.38
14:02:08	89.497
14:02:32	119.33
14:02:56	**129.27**
14:03:20	49.72
14:03:45	109.38
14:04:09	59.664

(a) Generated Speed

Received Time	Recorded Time	Message ID	Speed
14:03:27	14:02:44	SPEED ALERT	129.27

(b) Speed Alert

Table 3.2 Tested Speed Alert

Table 3.2 shows the generated speed data from the OBD-II Scan Application and the speed alert message in the OBD-II Test Server. Table 3.2 (a) is the logged table in the in-car application and Table 3.2 (b) is the logged table in the server application. The bold number in Table 3.2 (a) is the speed that is supposed to alert the headquarters about the speed. Table 3.2 (b) shows the logged speed alert message. The speed alert message is successfully transmitted via the Ethernet connection.

The DTC Alert functionality is also tested in the same condition. Whenever the OBD-II Scan Application detects the DTCs from the OBD-II Simulator, it transmits the DTCs to the server via the Ethernet connection. Table 3.3 shows the received DTCs in the OBD-II Test Server from the OBD-II Scan Application.

Received Time	Recorded Time	Message ID	DTCs
14:05:02	14:04:18	DTC ALERT	P1143 P0196 P0234
14:05:03	14:04:18	DTC ALERT	U0001

Table 3.3 Tested DTC Alert

3.3.3 Mileage and Fuel Mileage Test

Mileage and fuel mileage tests with many scenarios are performed with the OBD-II Simulator. The small errors for the tests are found even though it is the simulation condition. This is because of the data conversion between the simulator and the OBD-II Scan Application. Once we input the vehicle speed in mile on the OBD-II Simulator, it converts the vehicle speed into kilometer scale first, and then converts it into hexadecimal. The OBD-II Scan Application receives that hexadecimal, and it converts back to the integer in kilometer scale and finally converts into the mileage. Since there is conversion from integer to hexadecimal twice, some decimal points are dropped since hexadecimal does not accept decimal points in the OBD-II interface.

In the following, a few example scenarios are shown. MPH stands for Miles per Hour, GPH stands for Gallon per Hour, and MPG stands for Miles per Gallon.

Scenario One

The car starts moving at 60 MPH, 4GPH and running for 5 minutes and then it goes with 40 MPG, 2GPH for another 5 minutes (10 minute test)

The expected mileage is 5 miles when the car is traveling at 60 MPH, and 3.33 miles when the car is going at 40 MPH. Hence, the total expected mileage is 8.33 miles in this experiment. The tested mileage is 4.7731 miles when the car is traveling at 60 MPH, and 3.4473 miles for 40 MPH. The total tested mileage is 8.2204 miles. The error of the total mileage is 1.32%. The expected fuel consumption is 1.754% for 4 GPH (0.33 gallons), 0.877% for 2 GPH (0.167 gallons) in this scenario. The tested fuel consumption is 1.685 % for 4 GPH (0.32 gallons), 0.913% for 2GPH (0.173 gallons). Thus, the expected fuel mileage is 17.5 MPG and the tested fuel mileage is 16.733 MPG.

Scenario Two

The car starts moving at 60 MPH, 4GPH and it runs for 10 minutes and then, it is traveling at 40 MPG, 2GPH for another 10 minutes (20 minute test)

The second test is to see how accurate fuel mileage is. The expected fuel mileage is 17.5 MPG and the tested result is 16.661 MPG. The error is 4.8%.

Scenario Three
The car is traveling at 60 MPH and 4GPH (15 MPG) when Project54 is on for 5 minutes. When Project54 is off, the car consumes 4 gallons. Then the car's running with Project54 again for 5 minutes (10 minute test)
This test is to see how accurate the missing mileage algorithm on the OBD-II Scan Application works. The expected fuel mileage is 15 MPG and the expected additional mileage after the car consumes 4 gallons is 60 miles. The tested fuel mileage is 14.913 MPG and the tested additional mileage is 60.4489 miles. The error from the fuel mileage estimation is 0.5%. The error from the missing mileage estimation from the missing fuel and fuel mileage is 0.75%.

Scenario Four
The car is moving at 90 MPH and 7 GPH for 5 minutes. When computer is off, 4 gallons of gas are filled up. After full tank of gas, it is running again with 90 MPH, 7 GPH for 5 minutes. (10 minute test)
This test is to see how stable the missing mileage estimation and fuel level estimation on the OBD-II Scan Application no matter fuel level is filled up. The expected mileage is 12.85 MPG and the tested mileage is 12.794 MPG. There is no additional mileage to be added in the actual mileage after this test.

Scenario Five
The car starts when Project54 is on. 4 gallons of gas are filled up when Project54 is on after 5 minutes. The car is running with 30MPH and 3GPH. (10 minute test)
This test is to see how well the mileage estimation works when Project54 is on. Even though some gallons of gas are filled up, there is no action, which is expected. The expected fuel mileage is 10 MPG and the tested fuel mileage is 10.645 MPG.

Scenario Six
The car is not moving, but spending 1GPH for 3 minutes (3 minute test)
The purpose of this test is to see how well the mileage estimation works when the speed is 0 MPH. The expected mileage and fuel mileage is 0 miles, and 0 MPG respectively. The tested results are also 0 miles, and 0 MPG respectively.

Scenario Seven
The car is not moving, and spending 0GPH for 3 minutes (3 minute test)
This test is similar to Scenario Six, but the fact that the car is not consuming any gas. The expected MPG and tested MPG is matched which is 0 MPG.

Various tests are performed to confirm the functionalities on the OBD-II Scan Application by the OBD-II Simulator: the regular OBD-II data acquisition, Speed Alert, DTC Alert, Mileage Estimation, and Fuel Mileage Estimation. All the functionalities are successfully tested.

3.3.4 Road Test

Based on the successful results from the simulation, the road test is performed on September 9, 2005 for approximately three hours with a Ford Crown Victoria 2003 (Figure 3.24). All the functionality in the OBD-II Scan Application came out to be accurate except mileage estimation. Mileage on the OBD-II Scan Application was off comparing to the mileage on the dashboard by 1.7%. Mileage started from 2635 mileage on both the dashboard and the OBD-II Scan Application. However, at the end of the mileage reading on both, the OBD-II Scan Application estimated the 1.1 mile less than the mileage on the dashboard after driving 65.5 miles. The main reason of the 1.1 mile error seems to be the slow update of the vehicle speed since the vehicle speed was updated every 26 seconds in the OBD-II Scan Application. Thus, the mileage estimation will improve when the update gets faster than the current update.

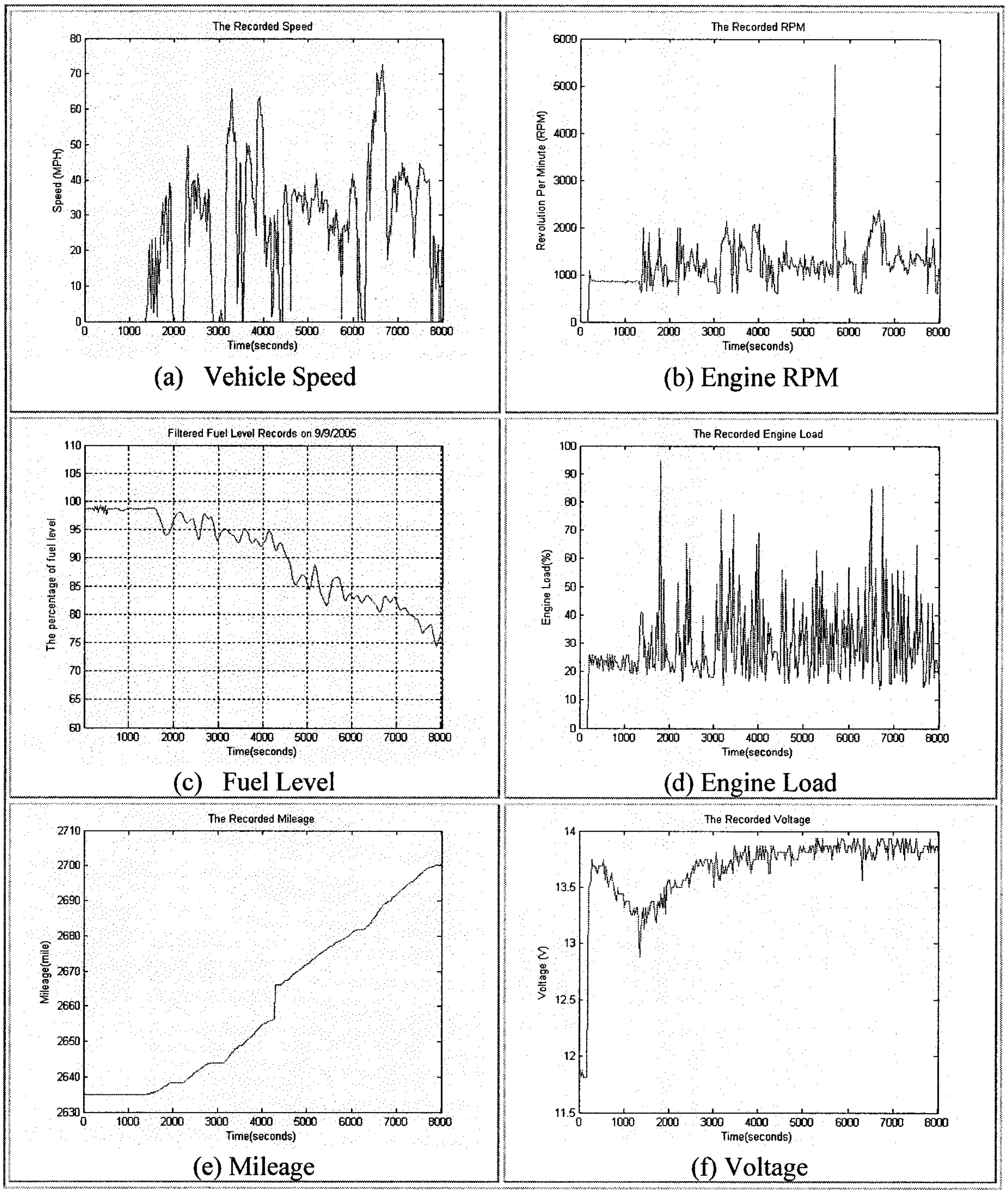


Figure 3.24 Recorded Vehicle Data on 9/9/05

Figure 3.24 (e) shows the mileage estimation. Around 4400 seconds, there is an instant mileage increment. The mileage estimation based on the fuel level information was performed at that time. When the Project54 system was restarted after being turned off enough to exceed the tolerance criterion, the OBD-II Scan Application estimated the missing mileage based on the missing fuel level. 9.67 miles were added automatically when the Project54 system was restarted. The driven mile on the dashboard was matched with the estimated mile in the OBD-II Scan Application. Thus, the OBD-II Scan Application added the missing mileage information in the mileage information successfully.

During the road test, the cellular service was also tested to connect the in-car application with the test server at UNH. The car was driven from UNH to Dover, Dover to Hampton Beach, and Hampton Beach to UNH. In these areas, the cellular service was disconnected most of the driving time. In fact, around Hampton Beach, the cellular service connection was hardly found. Moreover, it was hard to catch the cellular service signal while driving. Unfortunately, we may conclude that there are still many dead spots for the cellular service around New Hampshire and it makes even more difficult to connect to the cellular service while driving.

CHAPTER 4

POLICE RADIO TRAFFIC ANALYSIS

The other three proposed steps of this research deal with analyzing the NHDS radio traffic. To monitor police cruisers' status and locate using GPS information from the headquarters [19], the NHDS radio may be used since the NHDS radio can convey voice transmission, but also handle any digitized information [9]. Before utilizing the NHDS radio, the analysis is required to give a recommendation of sending the RVD and GPS data.

The NHDS radio is a conventional radio with a limited bandwidth designed for voice transmission. In contrast, a trunked radio is a radio system designed for an efficient bandwidth usage [9]. Thus, a trunk radio can handle more information than a conventional radio does. Extra data transmission such as GPS or RVD information may conflict with voice transmission in the current NHDS radio system. Therefore, a police radio traffic analysis is essential before sending the GPS and RVD data.

There are three main steps in an analysis of radio traffic: monitoring, modeling and simulating the radio traffic. First, radio traffic monitoring application has already been developed by Purmort [20] in CATLab. The application gets radio status messages from the radio and interprets the messages into the radio traffic information. Next, modeling must be done before simulating the radio traffic. We can model the radio traffic in terms of channel utilization, time pattern of use, and statistical distribution. Once we complete the radio traffic modeling, simulation can be performed based on the radio traffic model.

This chapter describes an analysis of the current police radio traffic. Section 4.1 describes the radio traffic monitoring and the radio traffic data processing required to be used in MATLAB program. Section 4.2 details Radio traffic modeling. Section 4.3 shows the simulation methods and the results.

4.1 Radio Traffic Data Monitoring and Processing

The fourth proposed step of this research was monitoring the current NHDS radio. Using Purmort's radio monitoring program [20], the New Hampshire State Police Troop A radio channel was monitored for 20 days (02/21/2006 to 03/12/2006) and the total number of the recorded transmissions was 149697 (the total number of the voice transmissions was 40689 and the total number of the data transmissions was 109008). The headquarters of Troop A is located in Epping, NH. Troop A serves two counties, which are Rockingham and Strafford. The sample data set that was gathered is shown in Table 4.1.

Type	ID	Date	Time	Duration
Data	A1TRP A	03/02/06	18:21:39.109	844
Data	A1TRP A	03/02/06	18:21:40.171	1000
Voice	112	03/02/06	18:24:28.562	1828
Voice	1000	03/02/06	18:24:33.93	2360
Voice	112	03/02/06	18:24:35.546	2844
Voice	1000	03/02/06	18:24:39.671	2375
Voice	112	03/02/06	18:24:42.312	19094
Voice	1000	03/02/06	18:25:05.187	1625
Data	A1TRP A	03/02/06	18:26:26.281	859

Table 4.1 Raw radio traffic data

The first field in the table indicates the type of the radio transmission. There are two different types: data and voice transmission. Voice transmission consists mostly of conversation between the headquarters and an individual police officer in a car. Data transmission is digitized information mostly for a motor vehicle check, hazardous materials check, and a variety of NCIC data checks [2]. The second field in the table indicates the ID that transmits the signal by individual users, including the dispatcher. In the collection of the police radio traffic, the data transmission is not identified. Thus, the IDs of all the data transmissions are the monitored channel name, which is "A1 Troop A." The third field shows the date. The fourth field is the time stamp. The last field indicates the transmission duration in milliseconds.

In order to analyze the data set in MATLAB, Three fields are converted from the text to the numbers: Type, Date, and Time. After the conversion, the converted sample data set is in Table 4.2 below.

Type	**ID**	**Date**	**Time (msec)**	**Duration (msec)**	**Inter-arrival time (msec)**
2	0	10	66099100	844	N/A
2	0	10	66100100	1000	1000
1	112	10	66268600	1828	168500
1	1000	10	66273900	2360	5300
1	112	10	66275500	2844	1600
1	1000	10	66279600	2375	4100
1	112	10	66282300	19094	2700
1	1000	10	66305100	1625	22800
2	0	10	66386200	859	81100

Table 4.2 Converted radio traffic data

The first field indicates the type of the radio transmission, but the indication is changed: number '1' indicates voice transmission and number '2' indicates data transmission. The second field indicates the individual ID. The ID '1000' is the dispatcher in 'A1 TRP A' channel. The ID, 'A1 TRP A', is changed into '0.' The third field is the recorded date. The fourth field indicates the converted time in milliseconds. The fifth field indicates the transmission duration in milliseconds. The last field indicates the inter-arrival time. Inter-arrival time is the time difference between the arrivals of each call. For instance, the third row of the inter-arrival time is 168500 milliseconds, which is the difference between the last call time, 66100100 milliseconds, and the current call time, 66273900 milliseconds (168500msec = 66273900msec - 66100100msec.)

4.2 Radio Traffic Modeling

The fifth proposed step of this research was modeling the NHDS radio traffic in terms of channel utilization, statistical distribution, and cyclic time pattern. First, channel utilization is examined in different perspectives. Second, both statistical distribution and cyclic time pattern are examined for each case of voice and data transmission.

4.2.1 Channel Utilization

Channel utilization of the NHDS radio traffic is examined in three different perspectives: Overall voice and data transmission, individual talker, and conversation.

4.2.1.1 Channel Utilization: Overall voice and data transmission

Using the converted radio traffic data set, the current channel utilization is examined. Channel utilization is the total channel usage time over the total monitoring time (4.1). Channel utilization can be expressed as percentages or Erlang [9]. If a channel is occupied by any type of voice or data transmission for six minutes and the monitoring time is an hour (60 minutes), then channel utilization is 10 % or 10 Erlangs.

$$Channel\_Utilization(\%) = \frac{The\_Total\_Transmission\_Duration}{The\_Total\_Monitored\_Time} \times 100 \quad (4.1)$$

The total duration of the data and voice transmission in 'A1 TRP A' channel is 251311901 milliseconds (approximately 69.8089 hours) out of 480 hours (20 days) where the average 1.678 hours per day of the voice transmission and the average 1.813 hours per day of the data transmission. Hence, the current usage of the channel is 14.54%. The outcome exceeds Purmort's results [20]. Purmort's result on the 'A1 TRP A' channel was 10.42%, where 2 hours per day of the voice transmission and 0.5 hour per day of the data transmission.

Table 4.3 shows the daily channel utilization from February 21st to March 12th. The maximum daily channel utilization is 0.1834 in the fourth day. On the other hand, the minimum daily channel utilization is 0.1012 in the sixth day.

Day	1	2	3	4	5
Channel Utilization	0.1666	0.182	0.1531	0.1834	0.18
Day	6	7	8	9	10
Channel Utilization	0.1012	0.114	0.1314	0.1169	0.1516
Day	11	12	13	14	15
Channel Utilization	0.1415	0.176	0.1441	0.1543	0.1455
Day	16	17	18	19	20
Channel Utilization	0.1358	0.141	0.14840	0.1363	0.1058

Table 4.3 Daily Channel Utilization

Figure 4.1 shows the hourly channel utilization. Each color of the line represents one of 20 different days. The X-axis is the hour and the Y-axis is the channel utilization in each hour. The discrete channel utilization data is displayed as a continuous curve in other to make the graph easier to view.

The maximum hourly channel utilization is 0.4566 at 7 A.M to 8 A.M in the twelfth day. On the other hand, the minimum hourly channel utilization is 0.0072 at 3 A.M to 4 A.M in the fourth day. By visual inspection, we see that there are the busy radio traffic hours at 7 A.M to 8 P.M, 2 P.M to 3 P.M, and 11 P.M to 12 A.M. Meanwhile, we see that at day time the radio traffic is busier than at night time.

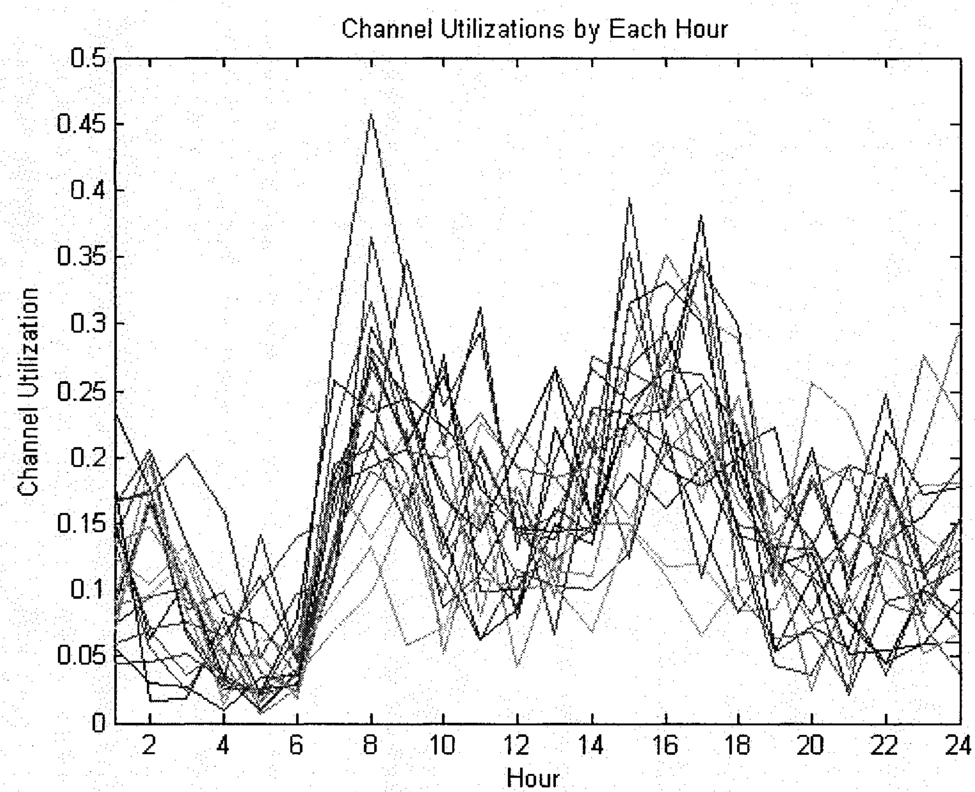


Figure 4.1 Hourly Channel Utilization

4.2.1.2 Channel Utilization: An Individual Talker

For the 20 day radio traffic monitoring, 217 individual ID units were identified in the 'A1 TRP A' channel including the dispatcher. Once all the channel usage of the voice transmission is divided by the number of units, each individual unit occupies 0.0338% of 'A1 TRP A' channel. Meanwhile, when the dispatcher's talk is eliminated from the total voice transmission, individual channel utilization is 0.0196%. The reason for the elimination of the voice transmission of the dispatcher is that dispatcher's voice transmission takes up the majority of the time on the radio.

The channel utilization by each unit of 'A1 TRP A' is less than Sprinkle's result [9], which is the channel utilization of 0.05%, where the average voice transmission traffic utilized by an individual user is 18 seconds per hour. There could be various reasons for the result that the 'A1 TRP A' channel utilization is less than Sprinkle's channel utilization. However, we may assume that the data transmission for the record check reduces the radio traffic since the data transmission is much more efficient than the voice transmission. The volume of the voice transmission and data transmission can be compared to prove the efficiency of the data transmission against the voice transmission. The voice transmission usually takes 10 to 15 seconds for any record check. On the other hand, the data transmission takes only a few seconds for any record checks. In fact, the maximum packet size of the data transmission is 512 bytes. Since the NHDS radio has 9600 bps capacity, it takes less than 0.43 seconds for one packet's delivery. Hence, we may conclude that the data transmission in Projec54 reduces the radio traffic dramatically.

4.2.1.3 Channel Utilization: Conversation

In consideration of placing the RVD or GPS data on the existing radio traffic, one condition of an assumption may be useful for the successful transmission of the RVD data or GPS without the interruption of the existing radio traffic. The condition is that we may not transmit any RVD data in any conversation period even though there is no channel usage while waiting for a response between two consecutive voice transmissions.

To define the unused time between two consecutive voice transmissions, the average data transmission on the radio traffic is first calculated. The reason to calculate the average data transmission is that the time duration is valueless for the data transmission between the two consecutive voice transmissions if the non-usage time duration is less than the average data transmission. The average data transmission is 1197.1866 milliseconds. Therefore, when waiting time of a response is less then 1 second, this time will not be useful.

The defined useless time durations are collected to be 6928419 milliseconds (1.92 hours out of 480 hours) between the voice transmissions. This result increases 0.404% occupancy of the channel so that the channel utilization becomes 14.944 %. When we throw away the time less than two seconds between the voice transmissions, the channel utilization is increased to 15.65 %. When we throw away the time less than three seconds between the voice transmissions, the channel utilization becomes 16.27 %.

The Industry Canada channel loading guidelines for land mobile radio systems used by safety services recommends below 50% channel utilization [21]. The 'A1 TRP A' channel utilizes about 15% of the time. The 'A1 TRP A' may use extra 35% channel utilization to transmit the RVD data or GPS data in the radio traffic.

4.2.2 Voice Transmission

This section characterizes the voice transmission on the radio traffic. Voice transmission can be fully expressed with two different time factor: duration time and inter-arrival time. Duration time is the period between the times any sender holds the push-to-talk button and the times any sender releases the push-to-talk button. Inter-arrival time is the length of time between the arrivals of two consecutive calls.

Once the duration time and inter-arrival time of police radio channel are collected, statistical analysis is performed to compare empirical data and mathematical distribution. Empirical distribution of police radio traffic is compared with a few mathematical distributions. Four theoretical distributions are chosen to compare with the empirical distribution: normal, exponential, lognormal, and Weibull distributions (Equation 4.2, 4.3, 4.4, and 4.5).

Each distribution has its own parameters. In normal distribution, θ represents the mean, and σ^2 represents the variance of its distribution. In exponential distribution, α and β are parameters deciding its starting point from zero and rate of decaying, respectively. Lognormal distribution is similar to normal distribution except its variables are taken by a log operation. In lognormal distribution, μ and σ^2 indicate the mean and variance, respectively. In Weibull distribution, α and β are scale and shape parameters, respectively.

$$Normal\_Distribution(t) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{1}{2\sigma^2}(t-\theta)^2 \right] \quad (4.2)$$

$$Exponential\_Distribution(t) = \alpha \cdot e^{t \cdot \beta} \quad (4.3)$$

$$Lognormal\_Distribution(t) = \frac{1}{t\sigma\sqrt{2\pi}} \exp\left[-\frac{(\ln(t)-\mu)^2}{2\sigma^2} \right] \quad (4.4)$$

$$Weibull\_Distribution(t) = \alpha \cdot \beta \cdot t^{\beta-1} e^{-\alpha \cdot t^{\beta}} \quad (4.5)$$

While transmission duration and inter-arrival time are continuous variables, we discretize them by counting up the instances of duration and inter-arrival time that fall within 100ms wide bins.

There are two different measurements to find out the best theoretical distribution fitting the empirical distribution among four. The Sum of Squares due to Error (SSE) (Equation 4.6) is to measure the total differences between the theoretical distribution (y_i) and the empirical distribution ($\hat{y}_i$). y_i and $\hat{y}_i$ are the probability parameters in each bin i which is 100 millisecond increment in our case. A SSE value closer to 0 indicates the better model of the police radio traffic. Meanwhile, R-Square is the square of the correlation between two distributions or it can be expressed with the SSE value (Equation 4.7). $\bar{y}$ is the mean of the empirical distribution in Equation 4.7. A R-Square value closer to 1 indicates the better model of the police radio traffic. In the MATLAB Curve Fitting Toolbox, the level of certainty can be chosen for the comparison between the theoretical and empirical distribution. In our case, the level of certainty was 95% where the empirical distribution is contained with the lower and upper prediction bounds of the theoretical distribution [22].

$$\mathrm{SSE} = \sum_{i=1}^{n} (y_{i.} - \hat{y}_i)^2 \quad (4.6)$$

$$R\_Square = 1 - \frac{\mathrm{SSE}}{\sum_{\mathrm{i=1}}^{\mathrm{n}} (y_i - \bar{y})^2} \quad (4.7) \left(\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i \right)$$

After a statistical analysis, cyclic time patterns may be recognized in the police radio traffic. Both duration and inter-arrival time are examined to recognize cyclic time patterns. First, duration is summed in each hour. The summed durations represent the total usage in each hour. Next, Spectrogram is performed. Spectrogram is the three dimensional graph that shows the frequency spectrum over the time [23]. Meanwhile, inter-arrival time is averaged in each hour. The averaged inter-arrival time in each hour shows how frequent the radio usage is. Spectrogram is also performed in the averaged inter-arrival time.

4.2.2.1 <u>Duration</u>

A. Statistical Distribution

Duration is characterized in statistical distribution. In the collected data, the average voice transmission duration is 3 seconds. The maximum voice duration is 120 seconds, whereas the minimum is 78 milliseconds. Figure 4.2 shows the histogram of the voice transmission duration categorized in each 100 millisecond bin. The empirical voice transmission duration distribution is normalized to compare with mathematical distributions (Figure 4.3).

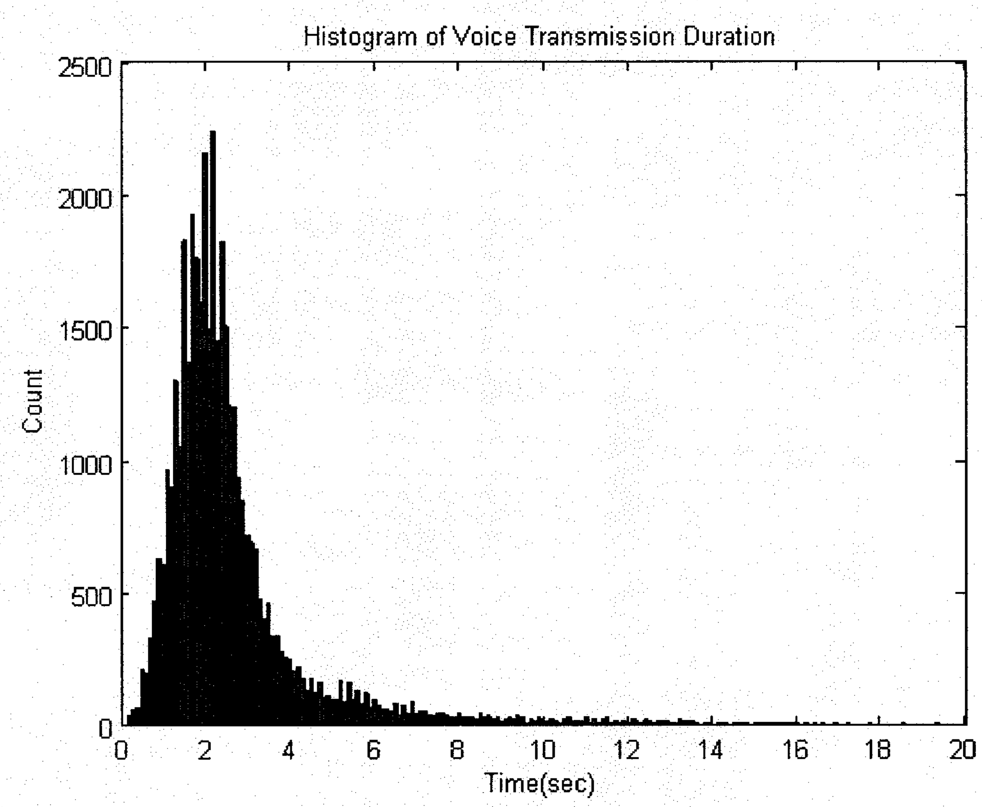


Figure 4.2 Histogram of Voice Transmission Duration

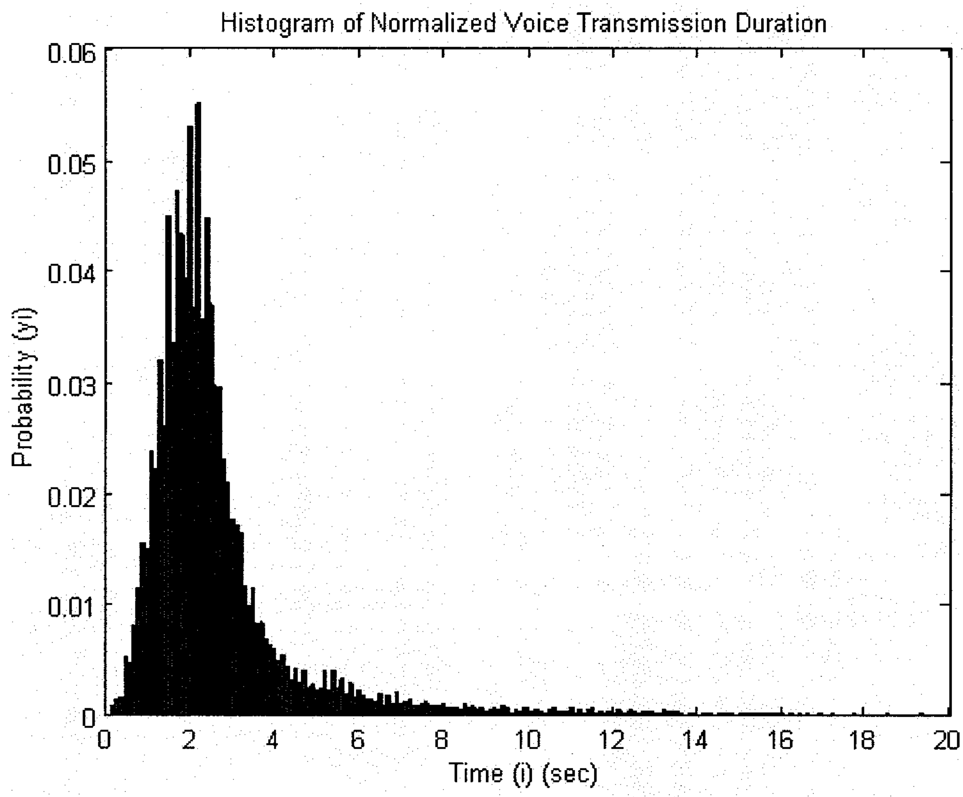


Figure 4.3 Histogram of Normalized Voice Transmission Duration

Four different theoretical distributions are chosen to compare with the normalized empirical voice transmission: normal, exponential, lognormal, and Weibull distributions (Equation 4.2, 4.3, 4.4, and 4.5). MATLAB Curve Fitting Tool 1.1 is used for the comparisons. Once the empirical voice transmission data is imported to the MATLAB Tool box, the four different mathematical formulas are chosen to compare with the empirical voice transmission duration. During the comparisons, the two measurements which are SSE and R-Square, and the parameters for each mathematical formula are automatically generated from the MATLAB Tool box.

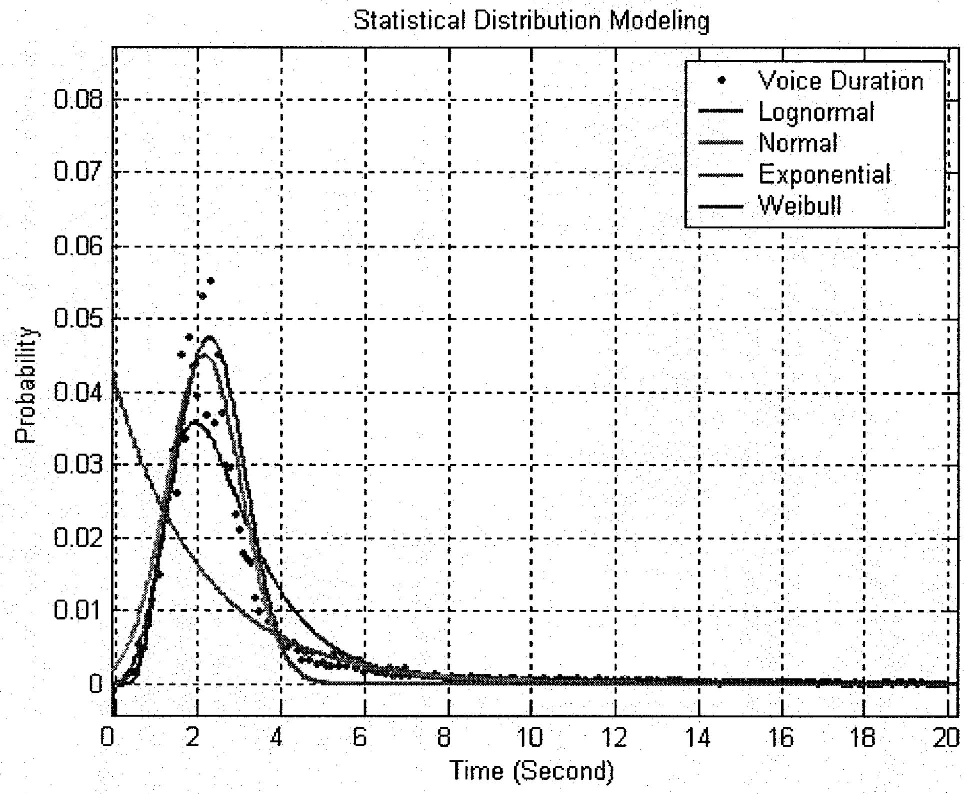


Figure 4.4 Statistical Distribution Modeling: Voice Duration

Theoretical Distribution	Parameters	Sum Square due to Error (SSE)	R-Square
Exponential	α= 0.04118 β= -0.04665	3.030e-004	0.9873
Lognormal	σ= 0.5081 μ= 3.213	6.079e-005	0.9974
Normal	σ= 8.848 θ= 21.45	1.315e-004	0.9945
Weibull	α= 3.943e-005 β= 3.125	1.316e-004	0.9945

Table 4.4 Comparison of Theoretical Distributions with Empirical Distribution

The distribution of the voice transmission duration appears to be 'Lognormal' distribution (Figure 4.3 and Table 4.4). The results of the SSEs and R-Squares show that the lognormal distribution is the closest fit to the empirical distribution of the police radio traffic.

Since the empirical distribution turns out to be the lognormal distribution, taking a log operation on the voice transmission duration gives us 'Normal' distribution (Figure 4.5) to find the mean and variance.

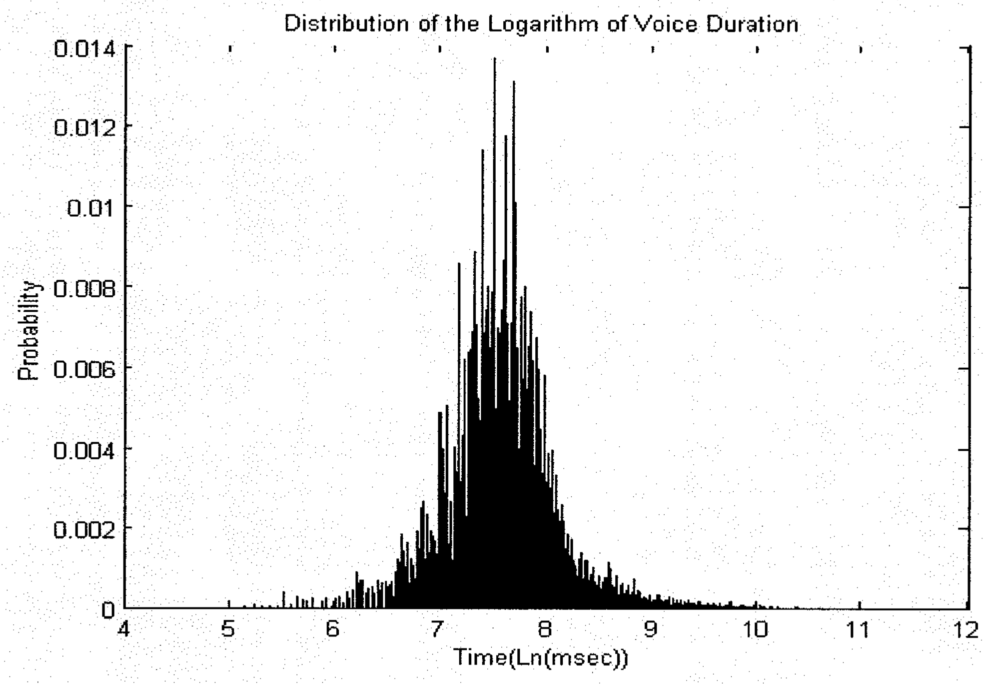


Figure 4.5 Distribution of the Logarithm of Voice Duration

Taken the log operation on the distribution of the voice transmission duration, the distribution becomes 'Normal' distribution.

$$Normal\_Voice\_Duration\_Distribution(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{1}{2\sigma^2}(x-\theta)^2\right] \quad (4.8)$$

Where the mean θ and variance σ^2 are 7.671 in unit of ln(msec) (note that $e^{7.671}$ milliseconds ≈2145 milliseconds) and 0.9263 in unit of $(\ln(m\sec))^2$ (note that $e^{0.9263}$

$(m\sec)^2 \approx 2.525\ (m\sec)^2$), respectively. x is ln(t), the natural logarithm of the voice transmission duration (milliseconds). The mean and variance are important parameters to characterize the distribution and may be used to create the model to simulate the radio traffic later on.

B. Cyclic Time Pattern

The usage of any police radio may have a cyclic time pattern. For instance, the radio traffic around 8 A.M may be busier than the radio traffic around 10 P.M. Under this assumption about the cyclic time pattern, the voice transmission duration is summed by each hour to see the usage of the police radio traffic.

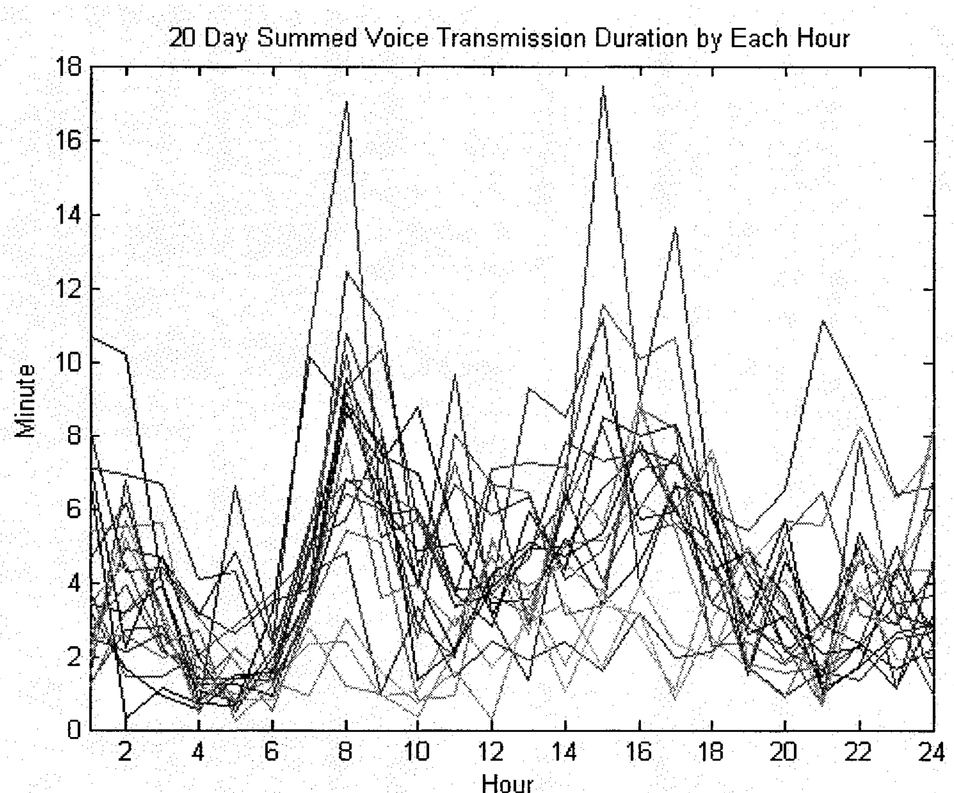


Figure 4.6 20 Day Summed Voice Transmission Duration by Each Hour

Figure 4.6 shows the summed voice transmission of the police radio in each hour. Each color of the line represents one of 20 different days. The X-axis is the hour and the Y-axis is the voice transmission duration which is summed by each hour. The discrete summed voice duration data is displayed as a continuous curve in order to make the graph easier to view. By visual inspection, we see that there are the busy radio traffic hours at 8 A.M, 4 P.M, and 12 A.M.

The number of the voice transmission in each hour is also counted. The plot of the voice transmission count is similar to that of the voice transmission duration. Figure 4.7 also shows the busy radio traffic hours at 8 A.M, 4 P.M, and 12 A.M. Due to the commuters' traffic on the road at 8 A.M, and 4 P.M, the busy radio traffic may be shown.

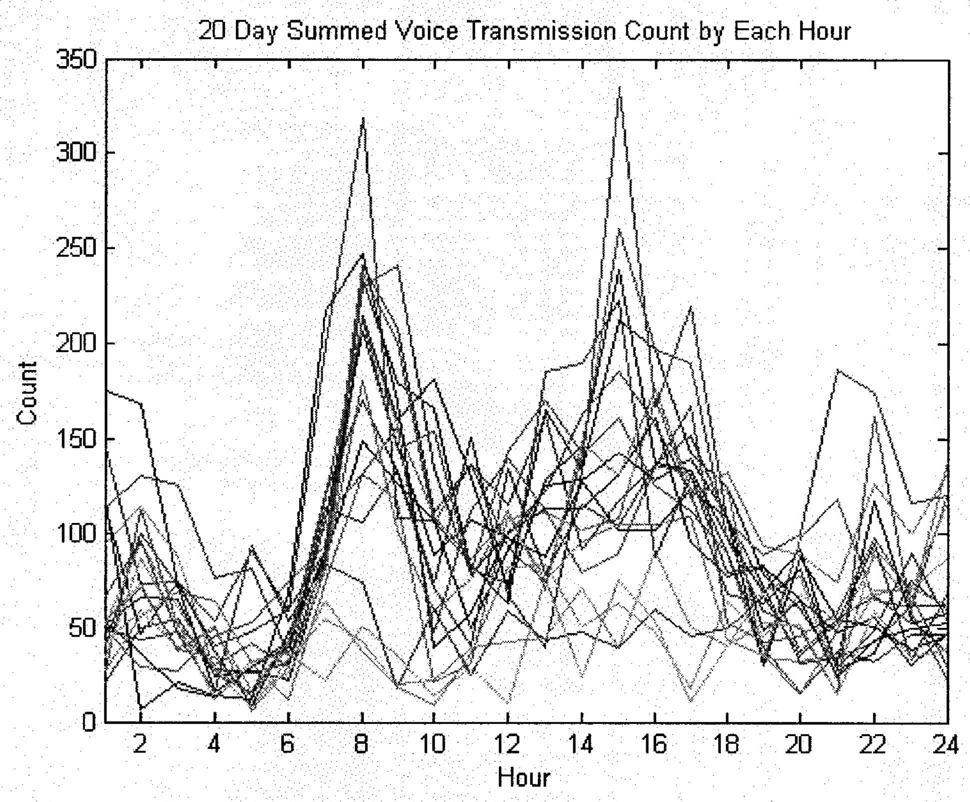
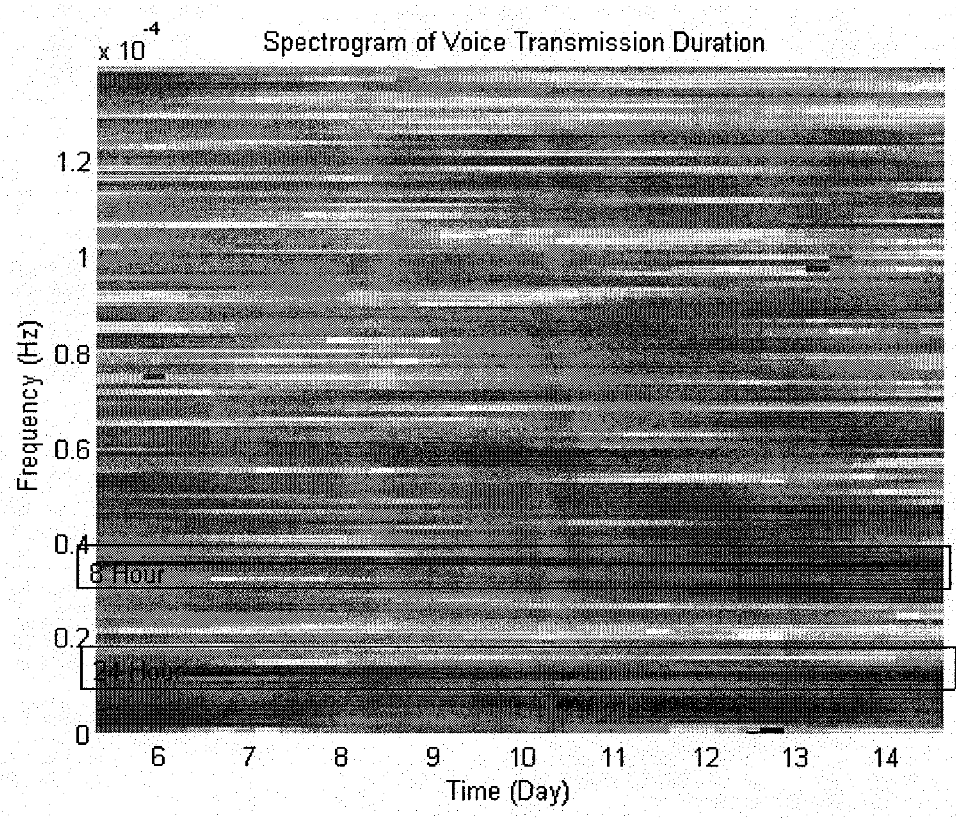


Figure 4.7 20 Day Voice Transmission Count

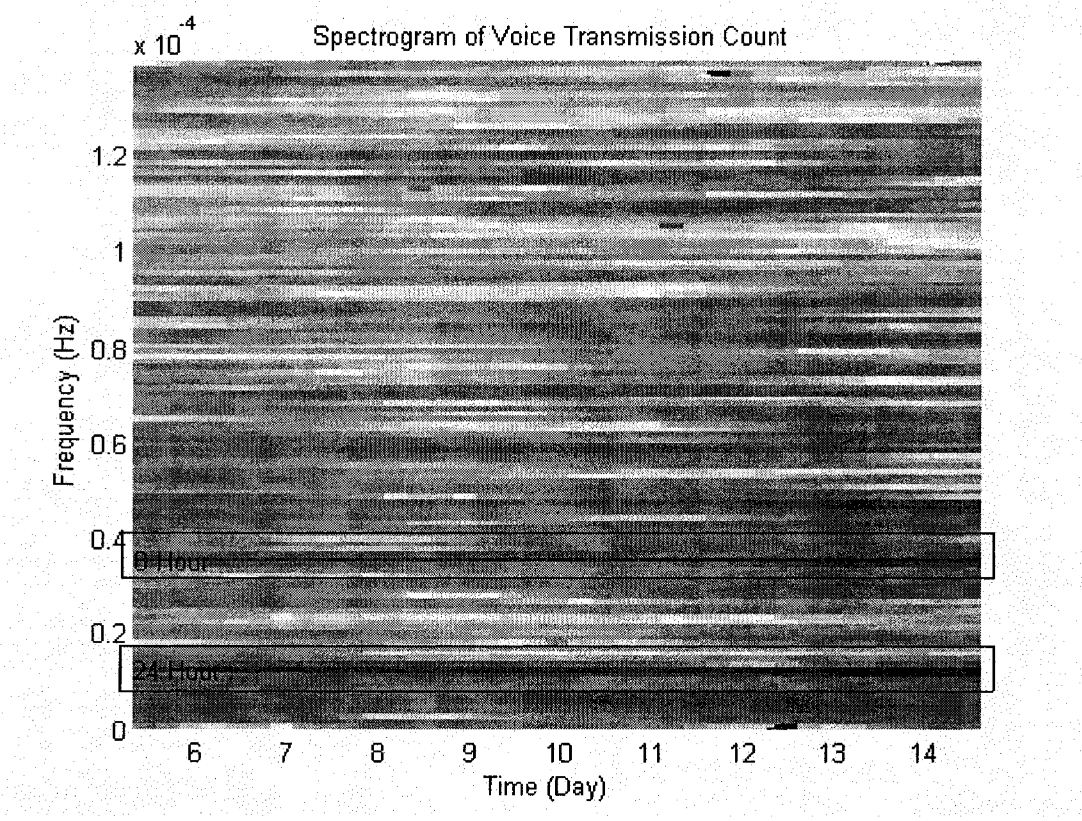
A spectrogram is applied on both the summed voice transmission duration and the voice transmission count in each hour. In MATLAB, a window size is determined to be 256, a number of overlapped data is to be 250, a number of sampling points to calculate Fast Fourier Transform (FFT) is 256, and the sampling frequency is 1/(60×60) Hz to show the cyclic time pattern.



(a) Spectrogram of Voice Transmission Duration

Figure 4.8 Spectrogram of Voice Transmission Duration

Figure 4.8 Continued



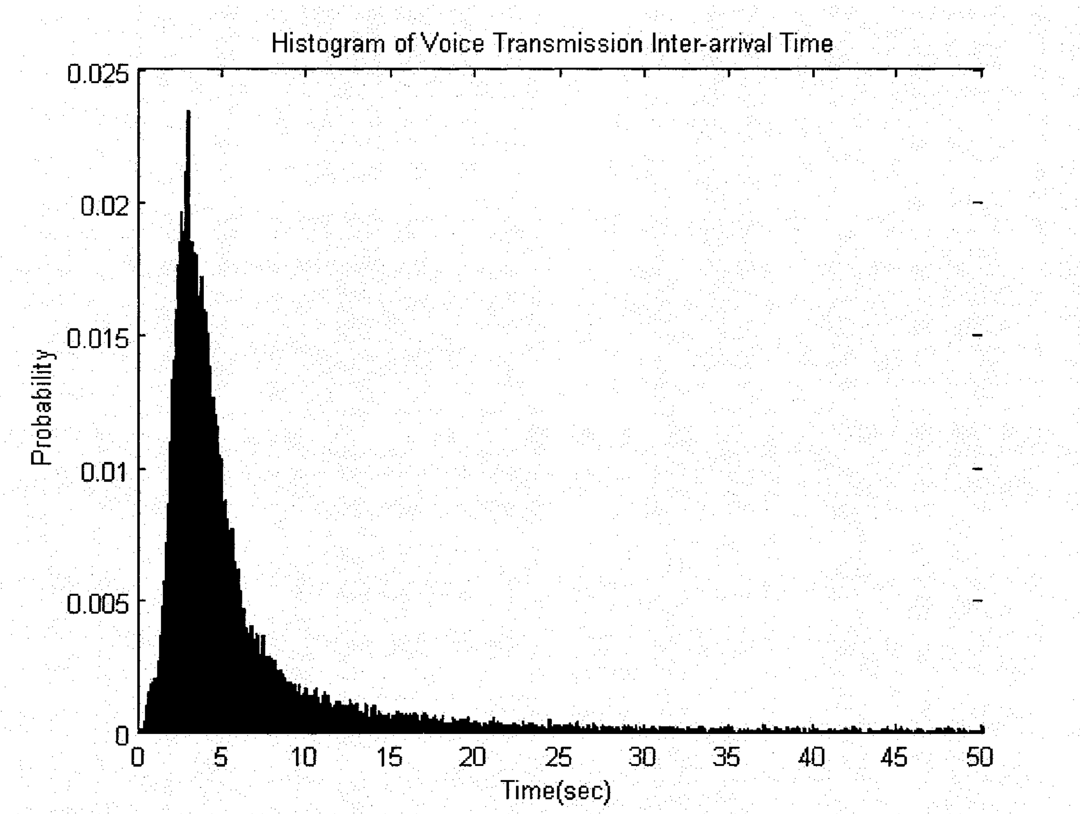
(b) Spectrogram of Voice Transmission Duration Count

As Figure 4.8 of the spectrogram of both voice transmission duration and count shows, there are two strong frequency components (0.35×10^{-4} Hz, 0.12×10^{-4} Hz) which are 8 hour and daily (24 hour) patterns. This result matches the clear evidence that there are 8 hour and daily patterns in the NHDS radio traffic than Figure 4.6 and Figure 4.7.

4.2.2.2 Inter-arrival time

A. Statistical Distribution

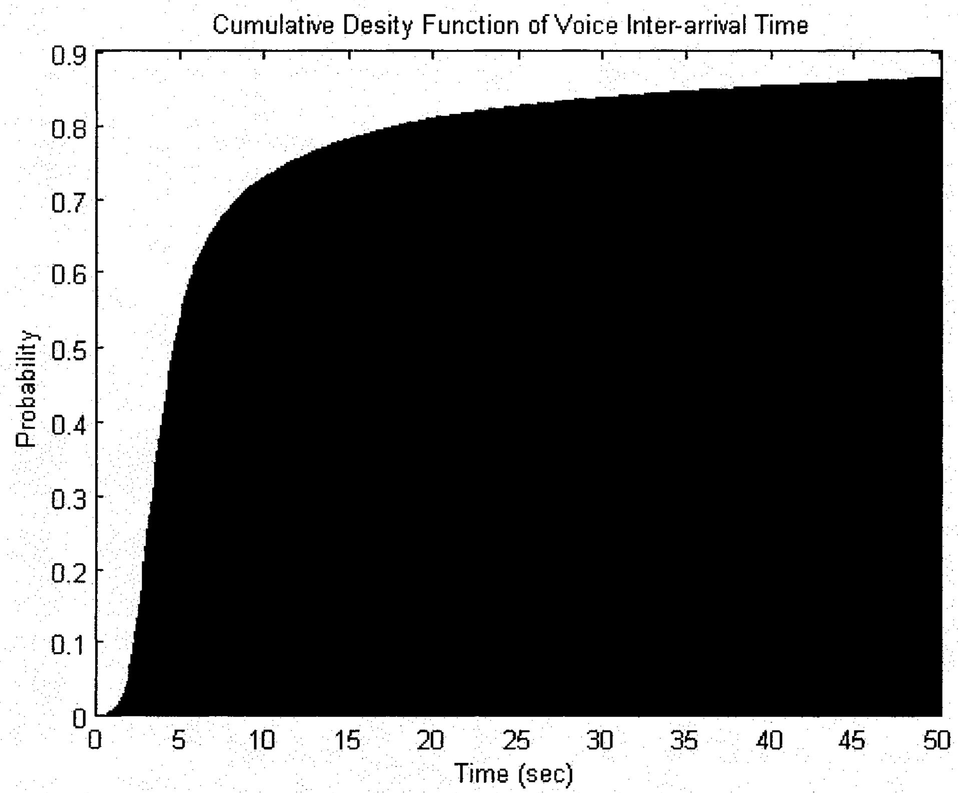
Inter-arrival time is defined as the time between two consecutive transmission arrival times. Figure 4.9 shows the histogram of voice transmission inter-arrival time categorized in each 100 millisecond bin and the cumulative histogram of voice transmission inter-arrival time. The empirical voice transmission inter-arrival time distribution is normalized.



(a) Histogram of Voice Transmission Inter-arrival Time

Figure 4.9 Histogram of Voice Transmission Inter-arrival Time

Figure 4.9 Continued



(b) Cumulative Histogram of Voice Inter-arrival Time

Four different theoretical distributions are chosen to compare with the empirical voice transmission: normal, exponential, lognormal, and Weibull distributions (Equation 4.2, 4.3, 4.4, and 4.5). The MATLAB Curving Fitting Tool 1.1 is also used for the comparison.

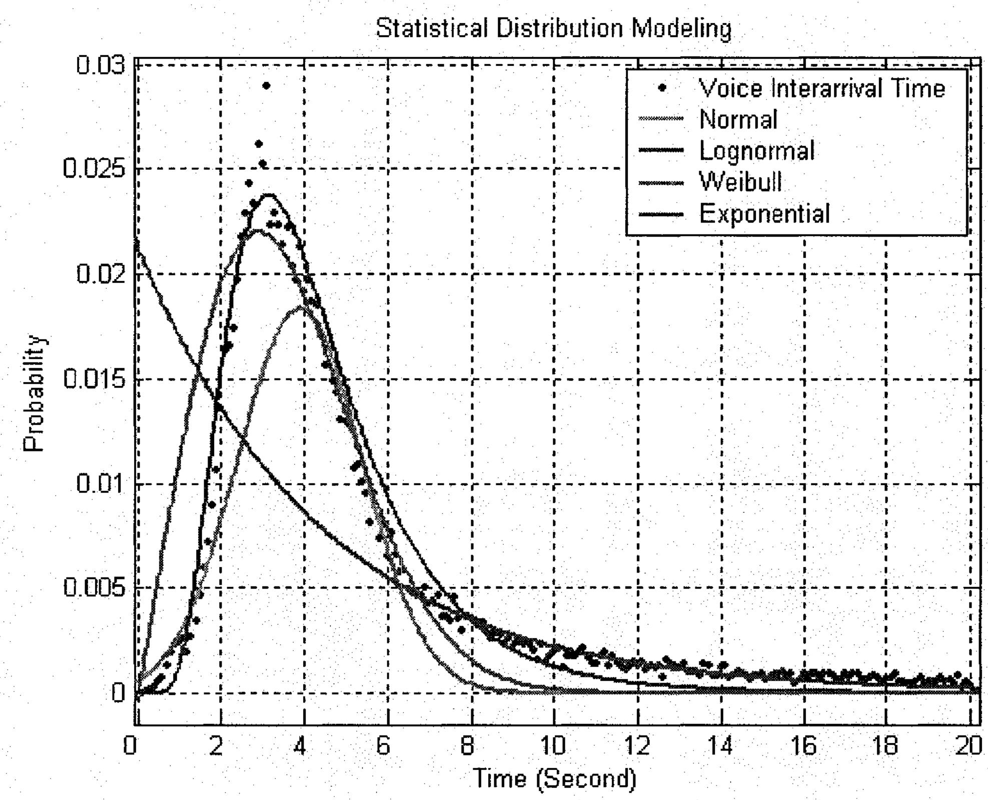


Figure 4.10 Statistical Distribution Modeling: Voice Inter-arrival Time

Theoretical Distribution	Parameters	Sum Square due to Error (SSE)	R-Square
Exponential	α= 0.02133 β= -0.02262	1.723e-004	0.9816
Lognormal	σ= 0.4796 μ= 3.67	3.244e-004	0.9654
Normal	σ= 4.65636 θ= 38.87	1.087e-003	0.8841
Weibull	α= 0.0004912 β= 2.068	6.380e-004	0.932

Table 4.5 Comparison of Theoretical Distributions with Empirical Distribution

Table 4.5 and Figure 4.10 show that the exponential distribution is the closest mathematical distribution to the voice inter-arrival transmission distribution. However, the lognormal distribution appears to be the closest to the empirical distribution since

70% of the voice inter-arrival time data are under 8 seconds (Figure 4.9 (b)). Thus, a natural log operation is taken on the voice inter-arrival time to find a mean and variance of the empirical distribution.

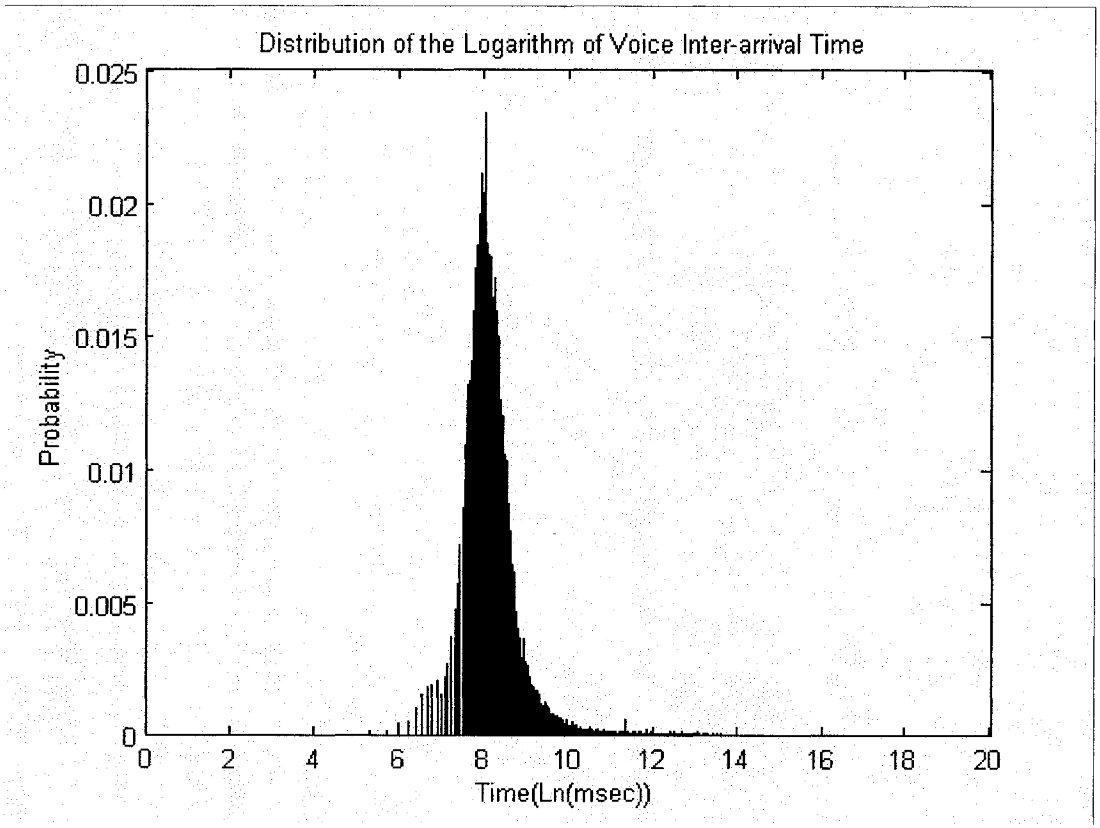


Figure 4.11 Distribution of the Logarithm of Voice Inter-arrival Time

The log operation on the voice transmission inter-arrival time is also performed (Figure 4.10). The mean and variance are the important parameters to characterize the police radio traffic and may be useful to simulate the police radio traffic later on.

$$Normal\_Voice\_Interarrival\_Distribution(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{1}{2\sigma^2}(x-\theta)^2\right] \quad (4.9)$$

Where the mean θ and variance σ^2 are 8.96 in unit of ln(msec) (note that $e^{8.96}$ milliseconds ≈7785 milliseconds) and 2.16 in unit of $(\ln(m\sec))^2$ ($e^{2.16}$ $(m\sec)^2 \approx 8.67$

$(m\sec)^2$), respectively. x is log(t), the logarithm of the voice transmission inter-arrival time (millisecond).

B. Cyclic Time Pattern

To recognize the cyclic time pattern with the inter-arrival time, the inter-arrival times were averaged in each hour and the Spectrogram is performed. The averaged inter-arrival time in each hour shows the frequency of the radio usage and represents the same information as the count of the transmissions. A shorter averaged inter-arrival time indicates more frequent radio usage.

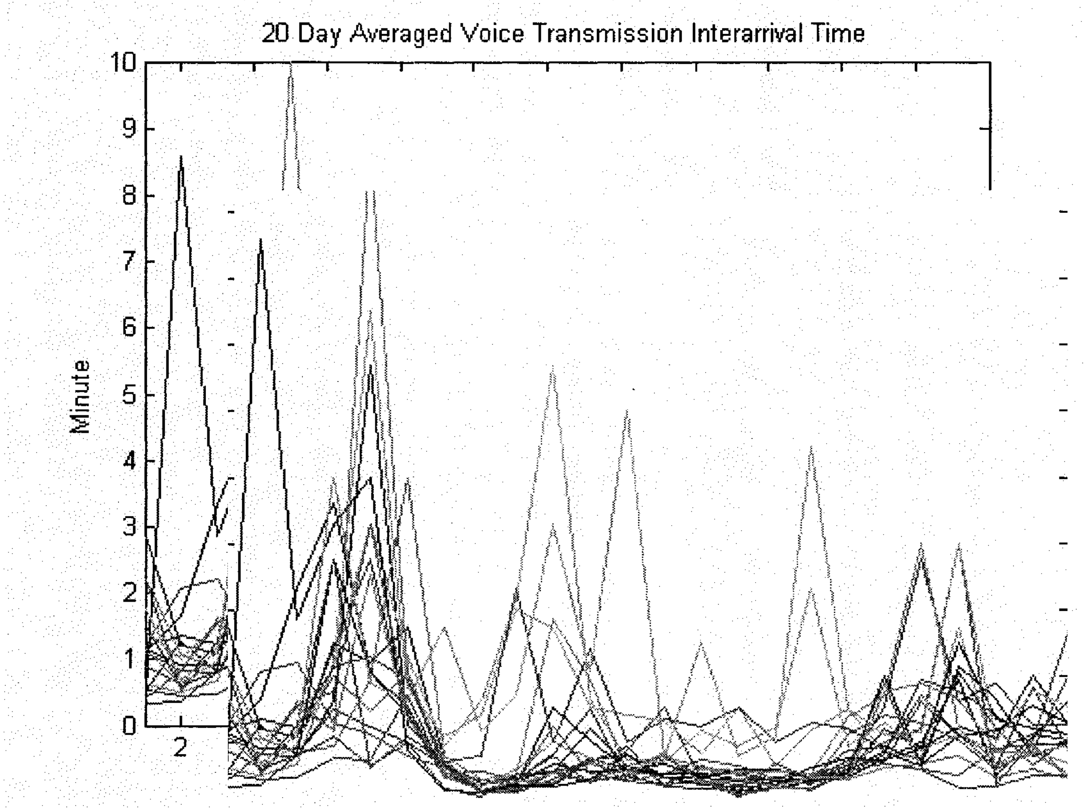


Figure 4.12 Averaged Inter-arrival Time

In Figure 4.12, each line in a different color represents a different day. However, it is hard to see the cyclic pattern in Figure 4.12. To see cyclic the pattern, the autocorrelation is applied first. Autocorrelation is a measure of dependence among variables. Autocorrelation is recognized graphically by plotting the autocorrelation in a range of lags. Correlation in variables exists either if the autocorrelation plot shows the pattern or if it decays slowly. In our case, the autocorrelation shows the pattern.

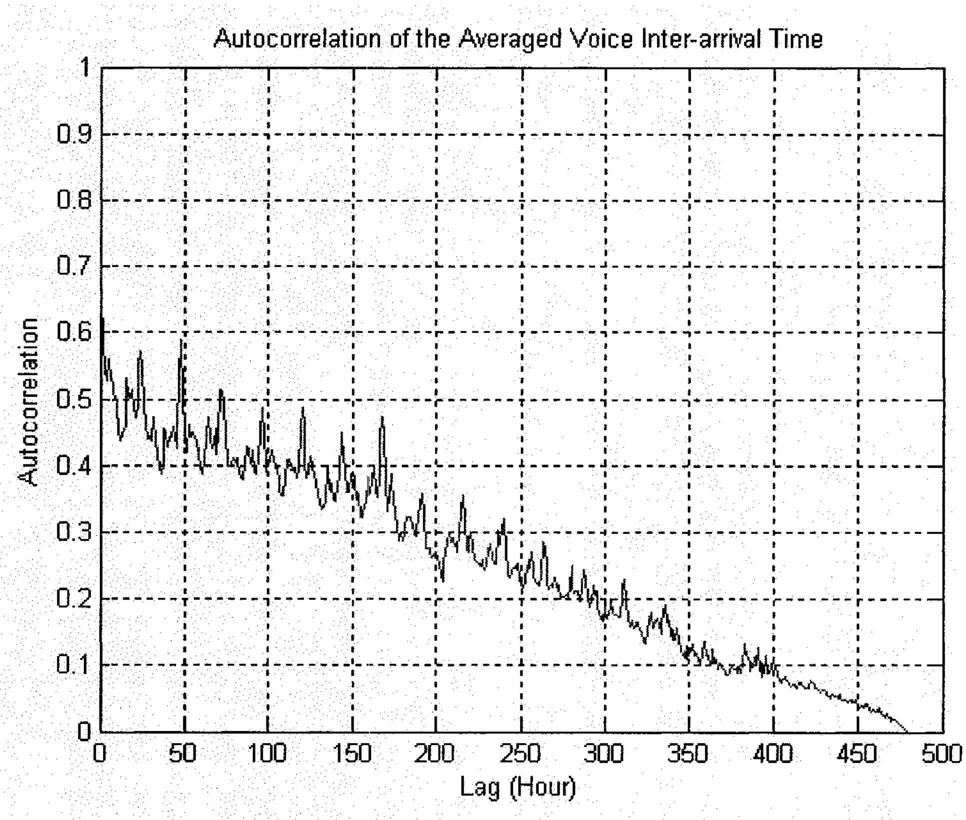


Figure 4.13 Autocorrelation of Voice Inter-arrival Time

As Figure 4.13 shows, the cyclic time pattern is shown in the autocorrelation. High peaks on the autocorrelation repeats at 24 hour lag and small peaks repeat at 8 hour lag. The Spectrogram shows the 4.8, 8, and 24 hour pattern (Figure 4.14). Again, the 8 hour pattern shows that there are the busy hours at 8 A.M, 4 P.M on the road due to the commuting drivers. The 24 hour pattern indicates that there is daily routine in the NHDS radio traffic. There is an insignificant 4.8 hour pattern in Figure 4.14. This time pattern may be caused by the busy lunch time around noon and again busy commuting time round 4 to 5 P.M. Thus, this one time pattern may be shown with the 4.8 hour pattern. In MATLAB, a window size is determined to be 256, a number of overlapped data is to be 250, a number of sampling points to calculate Fast Fourier Transform (FFT) is 256, and the sampling frequency is 1/(60×60) Hz to show the cyclic time pattern (Figure 4.14).

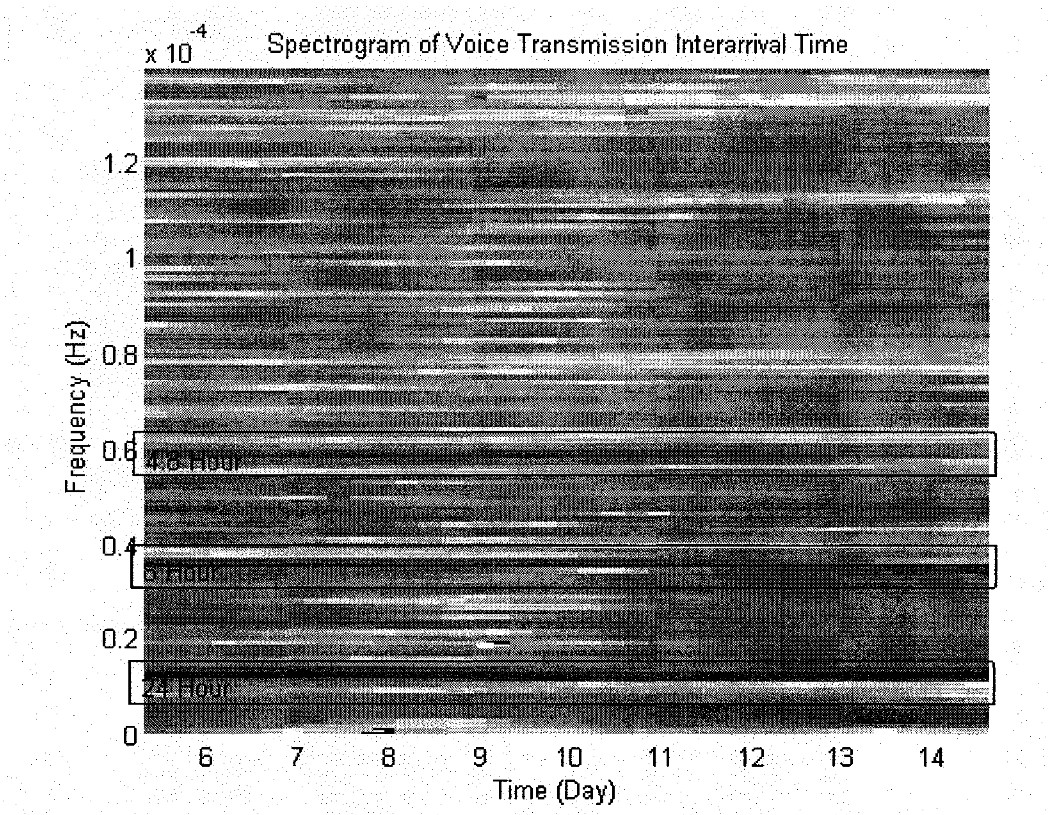


Figure 4.14 Spectrogram of Voice Inter-arrival Time

4.2.3 Data Transmission

This section characterizes the data transmission on the radio traffic. Data transmission can be also fully expressed with two different time factor: duration time and inter-arrival time. Statistical analysis and cyclic time pattern are also exercised in this section.

4.2.3.1 Duration

A. Statistical Distribution

The average duration of data transmission is 1.1 seconds. The maximum data duration is 12 seconds. However, it is impossible to have this average and maximum data duration since the maximum data packet size via the NHDS radio is 512 bytes which only takes 0.427 seconds with the 9600 bps radio. There is one possible explanation, which is that the resolution of the radio head controller is slow. Even though there are two consecutive data packets via the NHDS radio, the time between two packets is shorter than the resolution of the radio head controller. In other words, the radio head controller can not realize the short time between two consecutive packet deliveries. Thus, even though there is 12 seconds data duration, it may contain 30 consecutive packets without the long delay between them. The other explanation is that this 12 second data transmission may be the voice transmission containing the corrupted ID. Purmort's radio traffic monitoring application [20] classifies the voice transmission by recognizing the ID. If the ID is corrupted, then the application will classify the voice transmission as the data transmission.

Figure 4.15 shows the histogram of data transmission duration categorized in each 100 millisecond bin. The empirical data transmission duration distribution is normalized. The distribution of the data transmission duration appears to be two combined 'Normal' distribution.

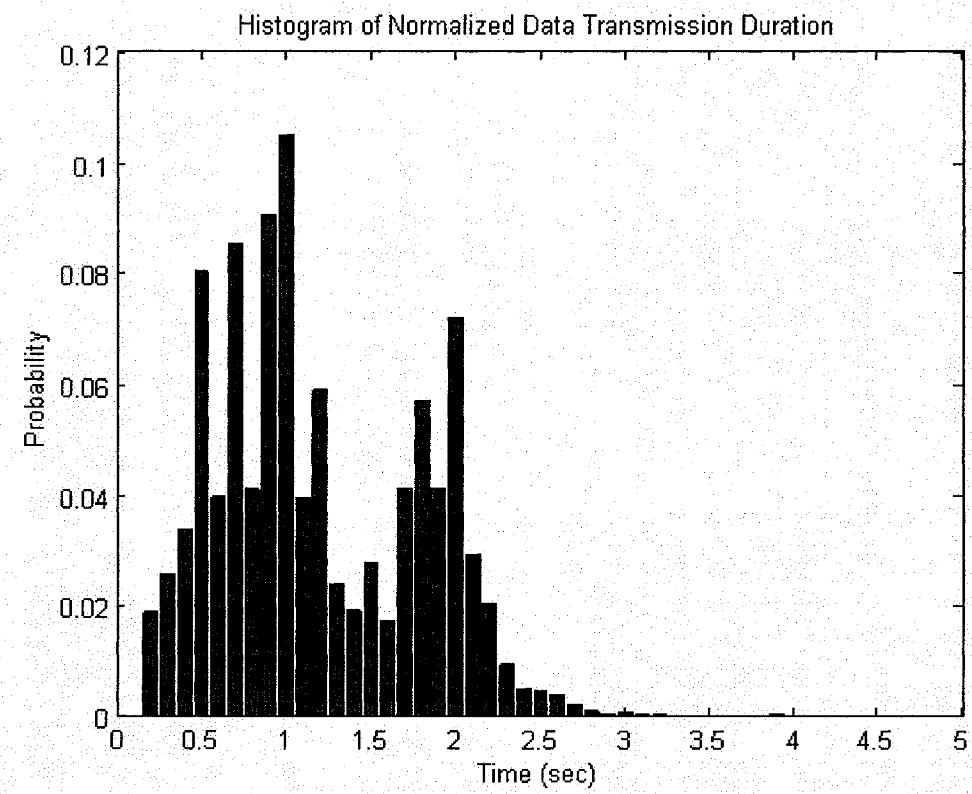


Figure 4.15 Histogram of Data Transmission Duration

The histogram of the data transmission duration time appears to be the two combined 'Normal' distribution (4.10).

$$Normal\_Distribution(t) = \frac{1}{\sqrt{2\pi\sigma_1^2}}\exp\left[-\frac{1}{2\sigma_1^2}(t-\theta_1)^2\right] + \frac{1}{\sqrt{2\pi\sigma_2^2}}\exp\left[-\frac{1}{2\sigma_2^2}(t-\theta_2)^2\right] \quad (4.10)$$

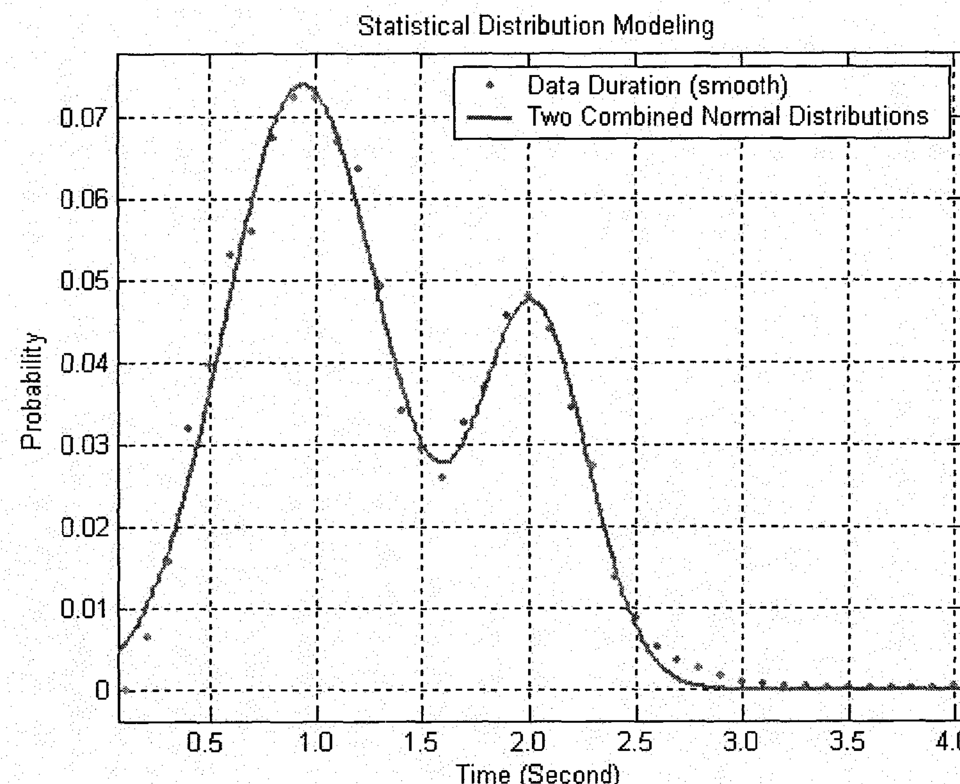


Figure 4.16 Statistical Distribution Modeling: Data Duration

Theoretical Distribution	Parameters	Sum Square due to Error (SSE)	R-Square
Normal	$\sigma_1 = 2.321$ $\sigma_2 = 2.930$ $\theta_1 = 9.398$ $\theta_2 = 20.18$	2.107e-004	0.9912

Table 4.6 Comparison of Two Combined Normal Distributions with Empirical Distribution

Figure 4.16 is to find out the parameters that describe the data transmission duration. The statistics of the data transmission duration is varying so that it is hard to find the fit of the model distribution. Thus, the curve of statistical data duration is smoothed out to be compared with two combined mathematical normal distribution. To smooth out the curve, moving average technique is used in MATLAB Curving Fitting

Tool 1.1. Moving average eliminates high frequency components, thus highlighting long term cycle. Table 4.6 shows the parameters of two combined normal distribution. Two high peaks are shown at 0.9 and 2.018 second data transmission.

B. Cyclic Time Pattern

Under the same assumption of the cyclic time pattern from the analysis of the voice transmission, the duration of the data transmission is summed in each hour.

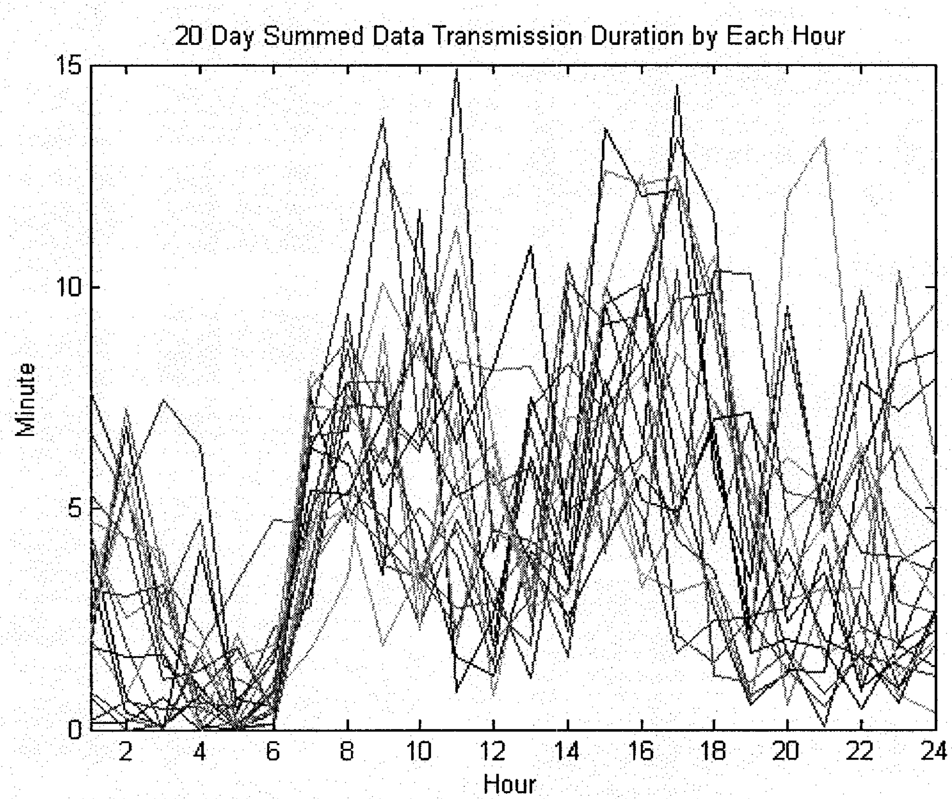


Figure 4.17 20 Day Summed Data Duration in Each Hour

Figure 4.17 shows the usage of the police radio, 'A1 TROOP A' with the summed data transmission duration in each hour. Each colored line represents each one of 20 different days. The X-axis is the hour and the Y-axis is the summed data transmission duration time in each hour. The cyclic time pattern of the data duration is similar to that of the voice duration. There are three peaks at 8 A.M, 4 P.M, and 12 A.M. This result may also be shown because of the heavy traffic due to the commuters.

The number of the data transmission in each hour is also counted and Figure 4.18 shows the similarity between the summed data transmission duration and the number of the data transmission in each hour.

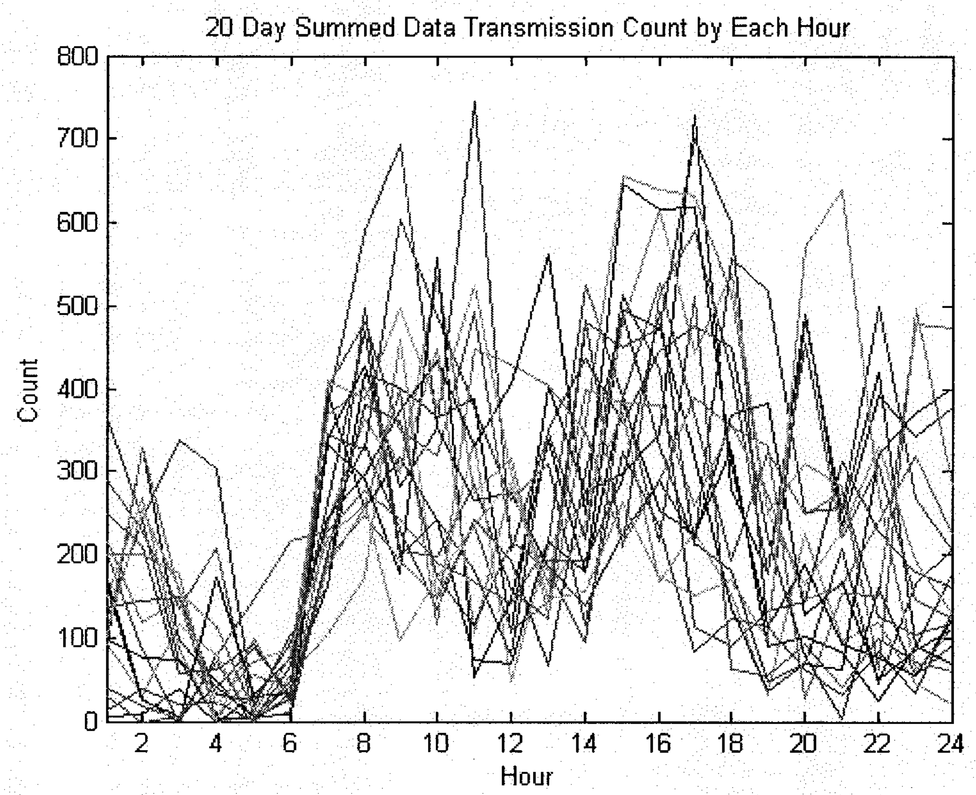
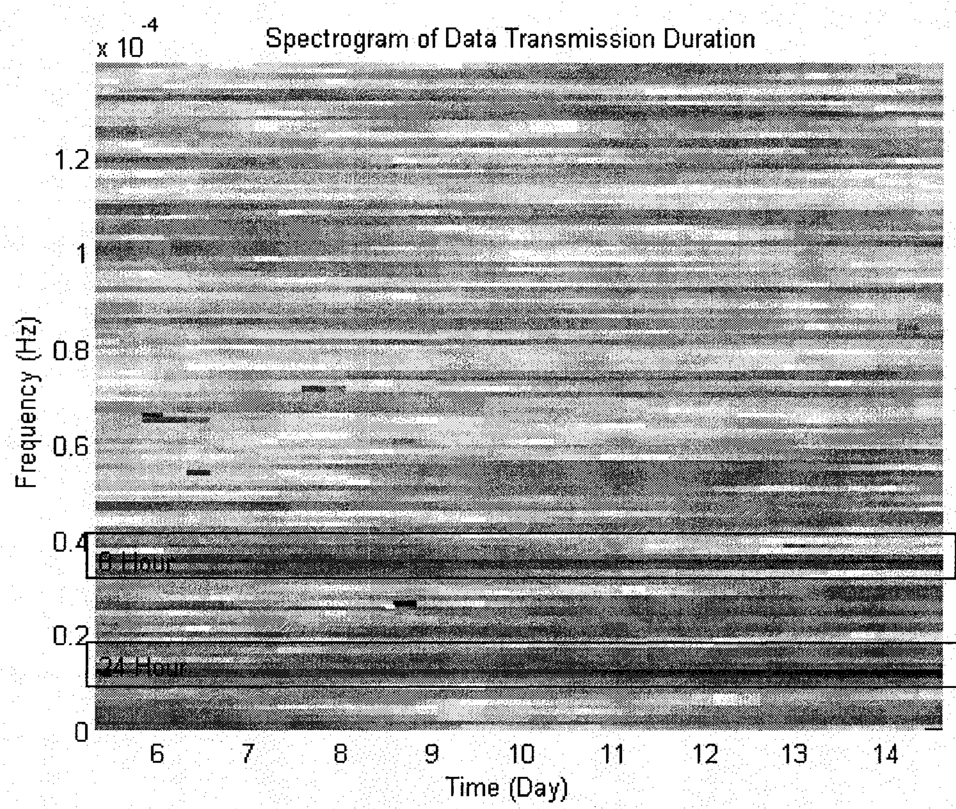


Figure 4.18 20 Day Data Transmission Count in Each Hour

The spectrogram is applied on both the summed data transmission duration and the data transmission count in each hour to recognize the cyclic time patterns. In

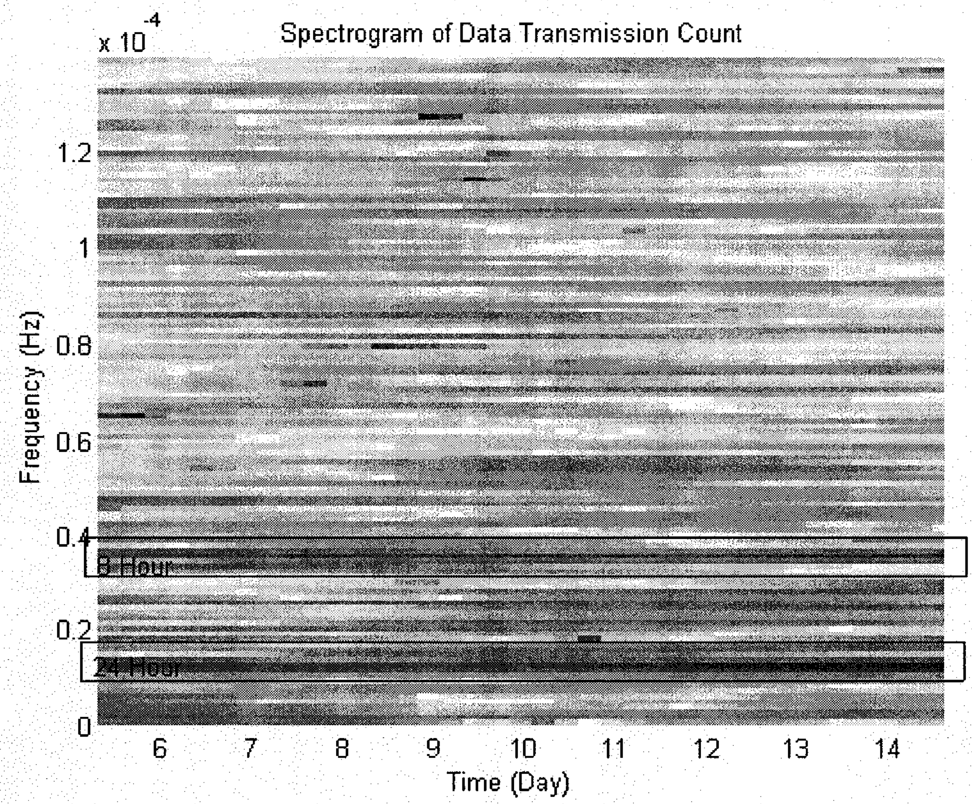
MATLAB, a window size is determined to be 256, a number of overlapped data is to be 250, a number of sampling points to calculate Fast Fourier Transform (FFT) is 256, and the sampling frequency is 1/(60×60) Hz to show the cyclic time pattern.



(a) Spectrogram of Data Transmission Duration

Figure 4.19 Spectrogram of Data Duration & Count

Figure 4.19 Continued



(b) Spectrogram of Data Transmission Count

As Figure 4.19 of the spectrogram of both data transmission duration and count shows, there are two strong frequency components (0.35×10^{-4} Hz, 0.12×10^{-4} Hz) which represent 8 hour and daily patterns. 8 hour and daily pattern of the data duration exist as well as that of the voice duration. 8 A.M, 4 P.M are busy hour due to commuters on the road.

4.2.3.2 Inter-arrival time

A. Statistical Distribution

Inter-arrival time is defined as the time between two transmission arrival times. Figure 4.20 shows the histogram of data transmission duration categorized in each 100 millisecond. The empirical distribution of the data transmission inter-arrival time is normalized (Figure 4.20).

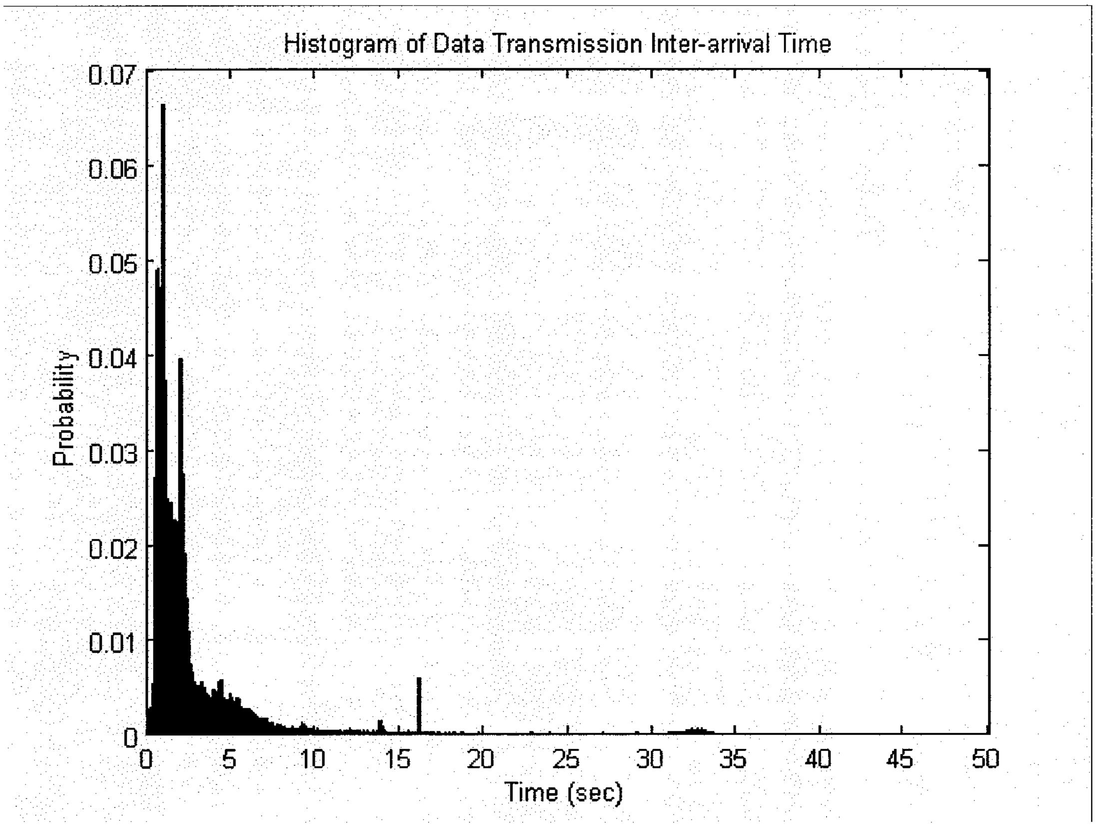


Figure 4.20 Histogram of Data Inter-arrival Time

The histogram of the data transmission inter-arrival time appears to be two combined 'Normal' distribution (4.11).

$$Normal\_Distribution(t) = \frac{1}{\sqrt{2\pi\sigma_1^2}} \exp\left[-\frac{1}{2\sigma_1^2}(t-\theta_1)^2\right] + \frac{1}{\sqrt{2\pi\sigma_2^2}} \exp\left[-\frac{1}{2\sigma_2^2}(t-\theta_2)^2\right] \quad (4.11)$$

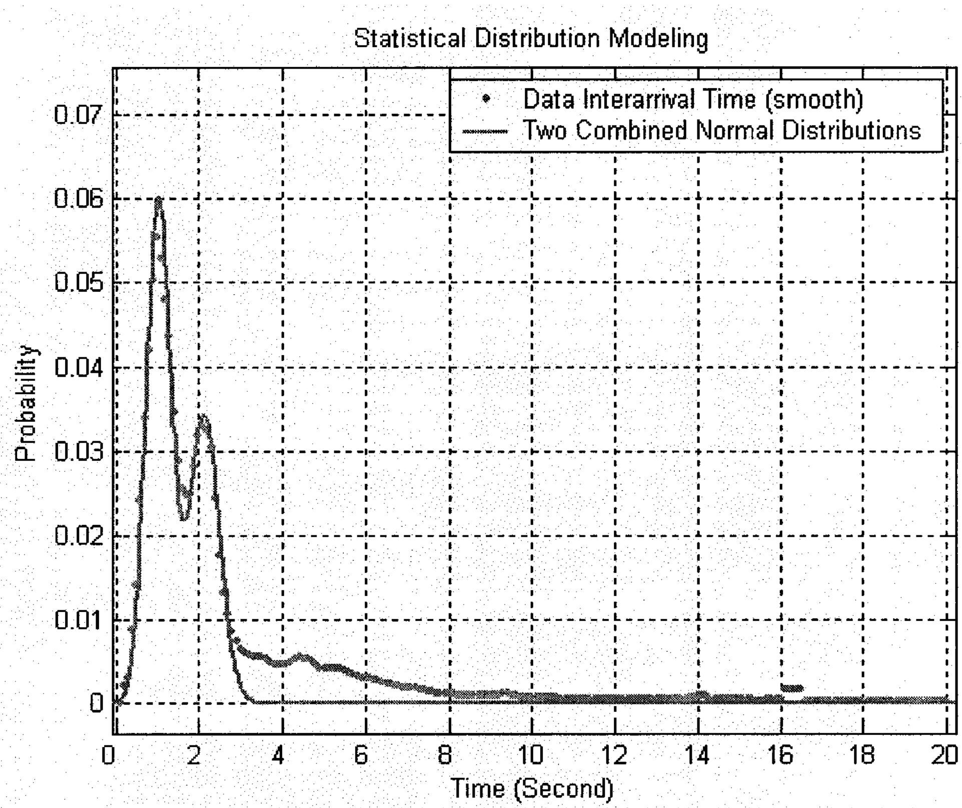


Figure 4.21 Statistical Distribution Modeling: Data Inter-arrival Time

Theoretical Distribution	Parameters	Sum Square due to Error (SSE)	R-Square
Normal	$\sigma_1 = 2.580$ $\sigma_2 = 3.410$ $\theta_1 = 10.28$ $\theta_2 = 21.24$	1.791e-003	0.9284

Table 4.7 Comparison of Two Combined Normal Distributions with Empirical Distribution

The curve of statistical data duration is smoothed out to be compared with the two combined normal distribution (Figure 4.21). To smooth out the curve, moving average technique is used in MATLAB Curving Fitting Tool 1.1. Moving average eliminates high frequency components, thus highlighting long term cycle. Table 4.7 shows the parameters of two combined normal distribution that fits the empirical distribution. There are two high peaks at 1.028 second and 2.124 second in Figure 4.21. The peak at one second is due to the fact that the Project54 server aims to send out the maximum one packet per second. Meanwhile, the peak at two second is the artifact that two consecutive packets are really close together so that the radio head control counts two packets as one. This result of the two consecutive data delivered without the delay is also shown in Table 4.8. Table 4.8 shows the typical sample of the radio traffic recording. The bold numbers show that data transmissions are close to each other so that the inter-arrival time of the data transmission is similar to the duration of the data transmission. In fact, the inter-arrival times are about 200~300 millisecond longer than the duration times.

Type	ID	Date	Time	Inter-arrival Time	Duration
Voice	130	03/04/06	12:45:32.781	2219	1578
Voice	1000	03/04/06	12:45:35.0	3781	1344
Data	A1TRP A	03/04/06	12:45:38.781	**1594**	**1343**
Data	A1TRP A	03/04/06	12:45:40.375	**1906**	**1657**
Data	A1TRP A	03/04/06	12:45:42.281	**859**	**640**
Data	A1TRP A	03/04/06	12:45:43.140	5719	1016
Data	A1TRP A	03/04/06	12:45:48.859	**2312**	**2078**
Data	A1TRP A	03/04/06	12:45:51.171	**1420**	**1188**

Table 4.8 Sample Radio Traffic Data

B. Cyclic Time Pattern

To recognize the cyclic time patterns with the inter-arrival time, the inter-arrival times are averaged in each hour and the Spectrogram is performed.

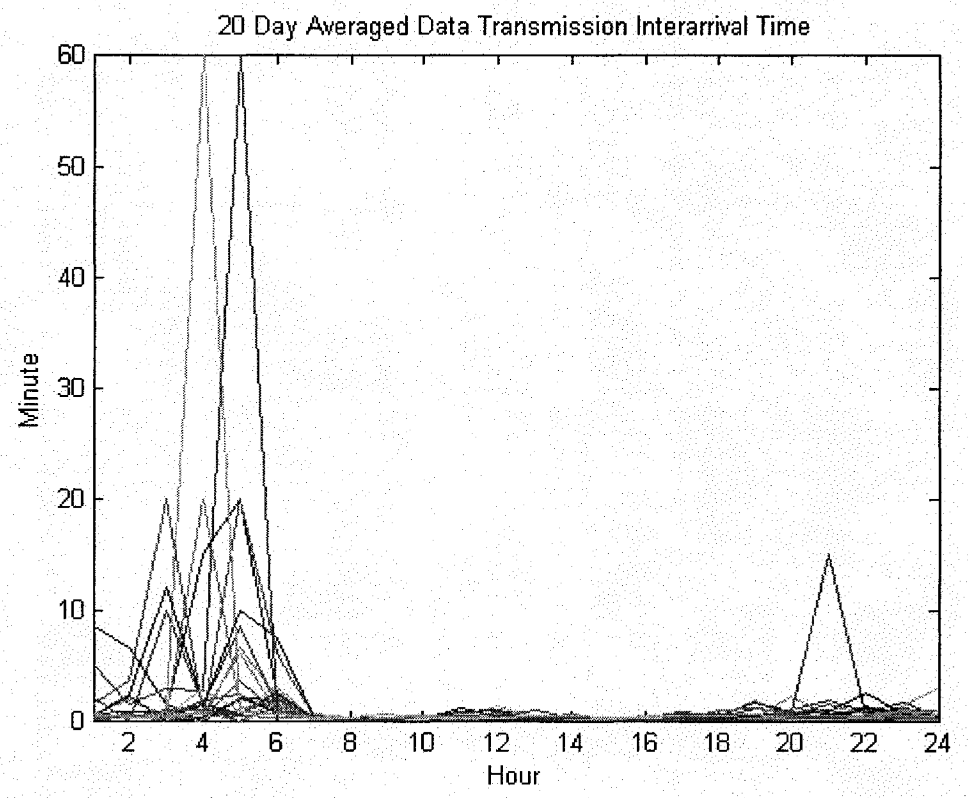


Figure 4.22 20 Day Averaged Data Inter-arrival Time

In Figure 4.22, lines of different colors represent each one of 20 different days. From 7 P.M until 7 A.M, the inter-arrival times are longer than the other time by visual inspection. This shows that from 7 P.M until 7 A.M, there are less activities of the NHDS radio traffic than from 7A.M to 7 P.M. The Spectrogram in MATLAB is used to identify the cyclic time pattern. Spectrogram shows the 8, 12 and 24 hour pattern (Figure 4.23).

New 12 hour pattern is also detected in this Spectrogram due to the time pattern from 7 P.M until 7 A.M since there is little activity during the 12 hour period between the hours of 7 P.M and 7 A.M. This appears to be a 12 hour pattern in Figure 4.22. In MATLAB, a window size is determined to be 256, a number of overlapped data is to be 250, a number of sampling points to calculate Fast Fourier Transform (FFT) is 256, and the sampling frequency is 1/(60×60) Hz to show the cyclic time pattern.

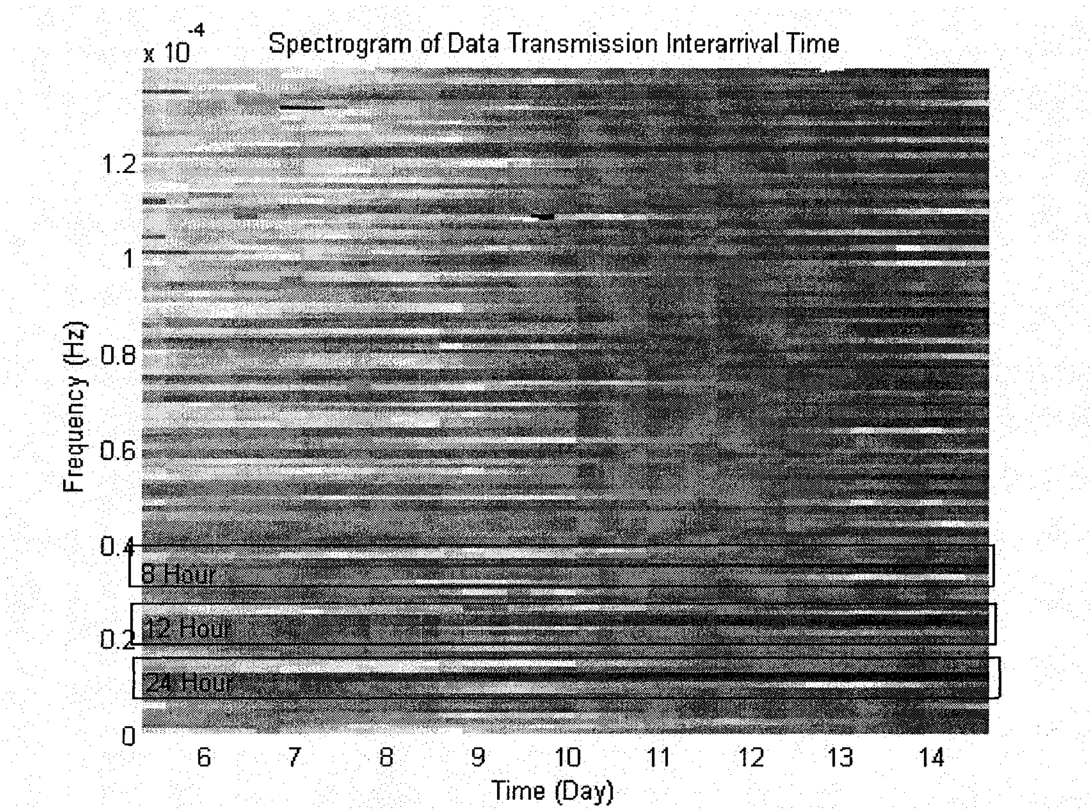


Figure 4.23 Spectrogram of Data Inter-arrival Time

4.3 Radio Traffic Simulation

The last proposed step of this research was simulating the transmission of the RVD and GPS data over the existing NHDS radio traffic. There are two scenarios for the RVD and GPS data transmission. From the results of two scenarios, the recommendations are made.

4.3.1 RVD Data Blocking Probability

To see how much RVD data can be sent without loss on the NHDS radio channel, the probability that the RVD data is blocked by existing radio traffic is calculated. There are two rules on the radio traffic applied in the simulation of the RVD data blocking probability. First, voice transmission always has priority to be sent over the radio traffic. Whenever data transmissions such as GPS data and the RVD data are sent over the radio traffic, they will be cut off if any voice activity is on the radio. Second, the RVD data is added immediately after the record check. Thus, whenever a police officer checks the record, the RVD data will be attached into this data transmission.

With the two rules, the simulation is performed on the real data traffic set in MATLAB. For each collected data transmission, we simply add more time duration to the current data duration and see if any data transmission duration is greater than the data transmission inter-arrival time when the voice transmission comes next. If it is, we assume that the transmission is blocked by the voice transmission and it will be discarded. If the data transmission comes next, we ignore this incident in this simulation. This is because only voice transmissions get priority over data transmissions.

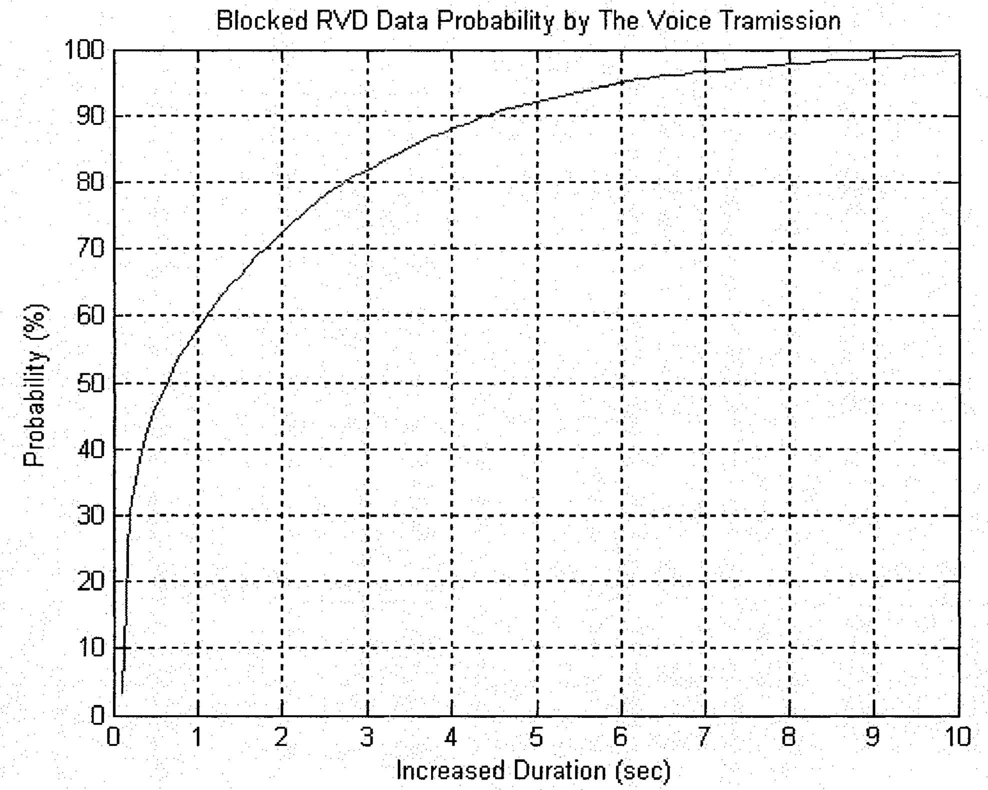


Figure 4.24 Blocked Remote Diagnostics Data by Voice Transmission

Figure 4.24 shows that the probability of the blocked RVD data by the voice transmission. The additional one second RVD data causes 58.13% blocking probability of the RVD data by the current voice transmission and it will increase the channel utilization of the NHDS radio traffic to 22.1%. Meanwhile, the additional two second RVD data is blocked about 72% of time by the current voice transmission and it will increase the channel utilization of the NHDS radio traffic to 29.7%. One possible reason of this high blocking probability is that at the busy hour (8 A.M and 4 P.M), both voice and data transmission are so frequent that there are many chance to be overlapped between them.

The recommendation of the RVD data transmission is that it is acceptable to send the one second RVD data attached to the data transmission. This is because even though the RVD data will be blocked about 60% of time by the voice transmission, the addition of the RVD data transmission to the current NHDS radio traffic does not exceed the recommended channel utilization [21], which is below 50%. Moreover, the RVD data is not emergency information, which requires to be sent right away.

4.3.2 GPS Blocking Probability

GPS data may be sent via police digital radio. Before the actual transmission, simulation is performed to see how much GPS data can be blocked by the existing transmission on the radio traffic, how often GPS data should be sent, and how many units can send the GPS data.

MATLAB is used to simulate the GPS blocking probability. First, 100 different cars sending the GPS data are created without the overlap time of each GPS data. In other words, we are simulating a scenario where the GPS transmissions from individual cruiser are synchronized so that they do not overlap each other. This is the best case scenario from the perspective of the GPS data transmission. In this simulation, various GPS data transmission rates from two minute time interval transmission to 15 minute time interval transmission are created. The duration of the GPS data transmission is assumed to be one second in the simulation because the average data transmission from the radio traffic is one second. Once the GPS data transmission is created, it is compared with the existing radio traffic. If the GPS data transmission conflicts with the existing radio traffic, this means that the GPS data transmission is blocked by the existing radio traffic. There are four different cases that the GPS data will be blocked by the existing radio traffic (Figure 4.25). However, four different cases can be expressed as two statements. In Figure 4.25, (a) and (b) can be expressed as an Equation 4.12. (c) and (d) can be expressed as Equation 4.13. First, when a GPS data transmission starts before a transmission starts on the existing radio traffic and that GPS data transmission ends after another transmission (voice or data) starts, the GPS data transmission is blocked by the existing radio traffic (Equation 4.12). Second, when a GPS data transmission starts after a transmission starts on the existing radio traffic and the starting point of the GPS data transmission is inside of any transmission duration, the GPS data transmission is also blocked by the existing radio traffic (Equation 4.13).

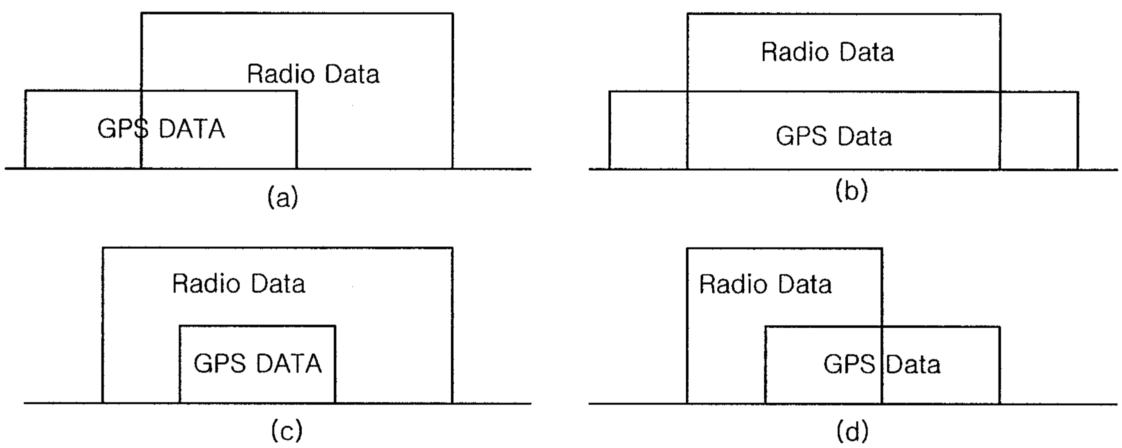


Figure 4.25 Four Different Scenarios of GPS Data Blocking by Existing Radio Traffic

$$t_{GPS\_start} < t_{Radio\_start} \text{ and } t_{GPS\_end} > t_{Radio\_start} \quad (4.12)$$

$$t_{Radio\_start} < t_{GPS\_start} \text{ and } t_{Radio\_end} > t_{GPS\_start} \quad (4.13)$$

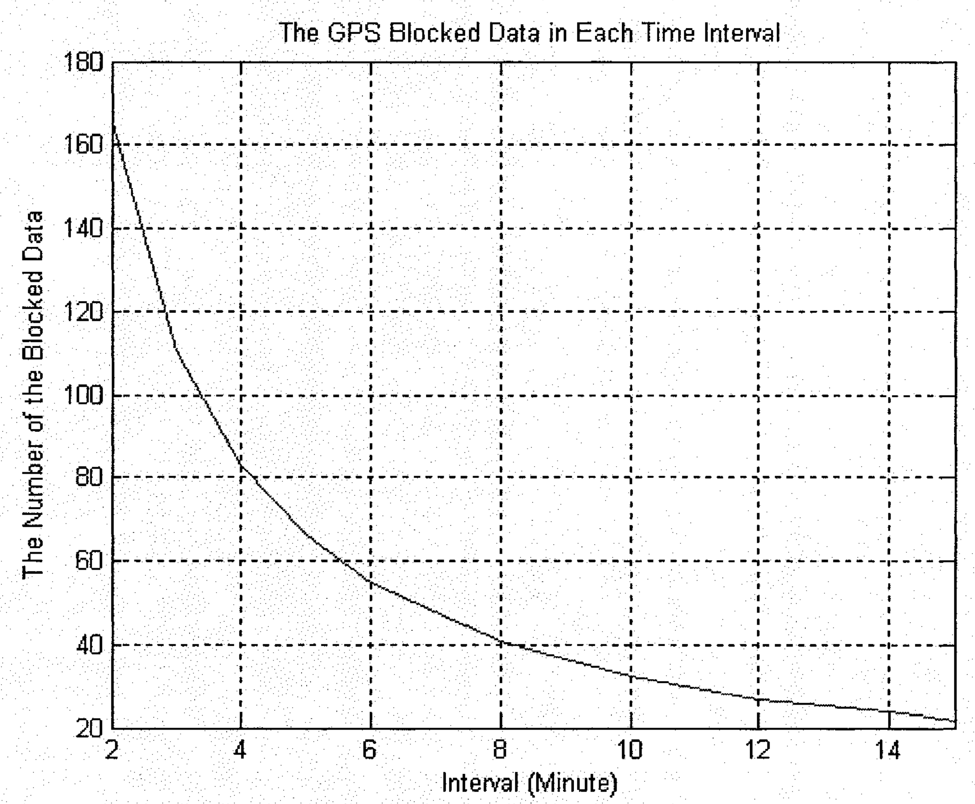


Figure 4.26 Number of the Blocked GPS Data by Existing Radio Traffic

In the simulation, the blocked GPS data from each car are counted in each day. Figure 4.26 shows the averaged number of blocked GPS data from each car by the existing radio traffic in each day. All the blocked GPS data from 100 different cars are divided by the number of the cars and again divided by the number of days. The reason that the blocked GPS data are divided by the number of the cars is that the variance of the numbers of the blocked GPS data from each car is small. In other words, the similar numbers of the blocked GPS data are counted from each car in each day. The result shows that the more frequent GPS data transmission causes the more blocked GPS data by the existing radio traffic. Average 165.492 GPS data are blocked in each day when two minute time interval of the GPS transmission whereas average 82.96 GPS data are blocked in each day when four minute time interval of the GPS transmission. When the GPS data are transmitted in two minute interval and four minute interval, the total numbers of the GPS data transmission for a day are 720 and 360, respectively. Thus, the GPS blocking probabilities for two and four minute interval are 22.96% (165.492/720) and 23.4% (82.96/360), respectively. We can say that the GPS blocking probability is almost constant no matter how frequent the GPS data is sent.

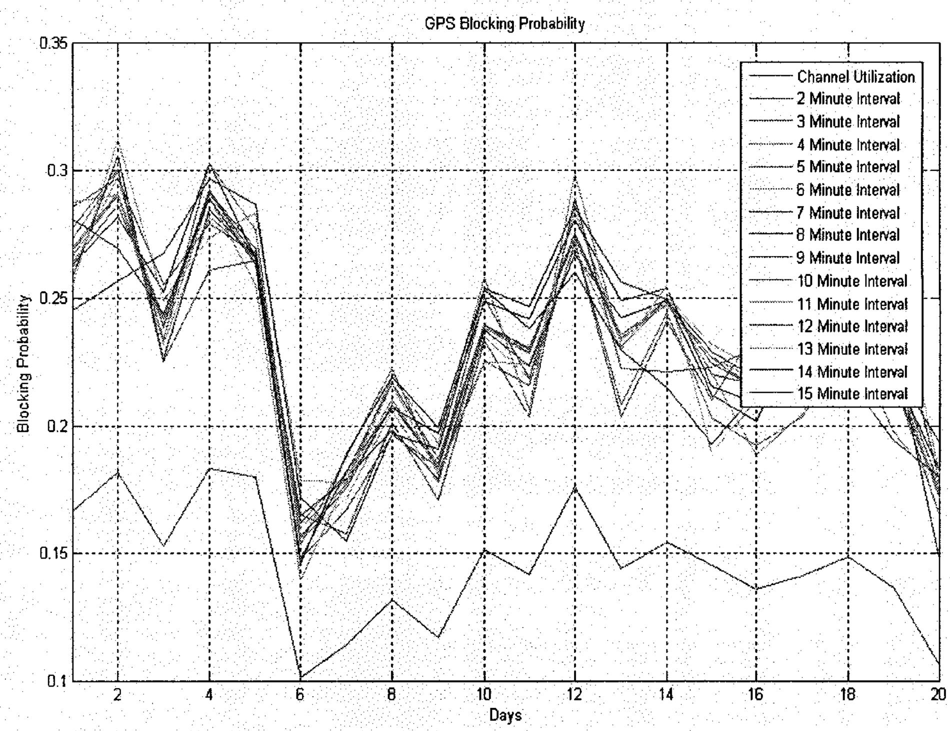


Figure 4.27 GPS Blocking Probability in 20 Days (1 Second Duration)

Figure 4.27 shows the probability that the GPS data from 100 cars are blocked by the existing radio traffic (both data and voice transmission). The blocked GPS data from 100 different cars are counted and divided by the total number of the GPS data transmission to have the GPS blocking probability. The probability is averaged for 100 different cars in each day. Fourteen colored lines represent how often the GPS data are sent from two minute to 15 minute intervals. Figure 4.27 confirms that the GPS blocking probabilities for different time intervals are almost same no matter how frequent the GPS data is sent since all the lines in the plot are very close to each other. Meanwhile, Figure 4.27 and Table 4.3 show that no matter how often the GPS data is sent, the probability of the blocked GPS data by the existing radio traffic is proportional to the channel utilization on the daily data. For instance, the blocking probability in Day 6 is lower than any other day since the channel utilization in Day 6 is lower than any other day. To confirm the proportionality between the blocking GPS probability and the channel utilization, the simulation of the two second GPS duration data is performed in all the same conditions as the one second GPS duration data simulation. Figure 4.28 shows the GPS blocking probability when the duration is two second. The probability when the duration is two second is about 10% higher than when the duration is one second. However, Figure 4.28 confirms that the GPS blocking probability is proportional to the channel utilization.

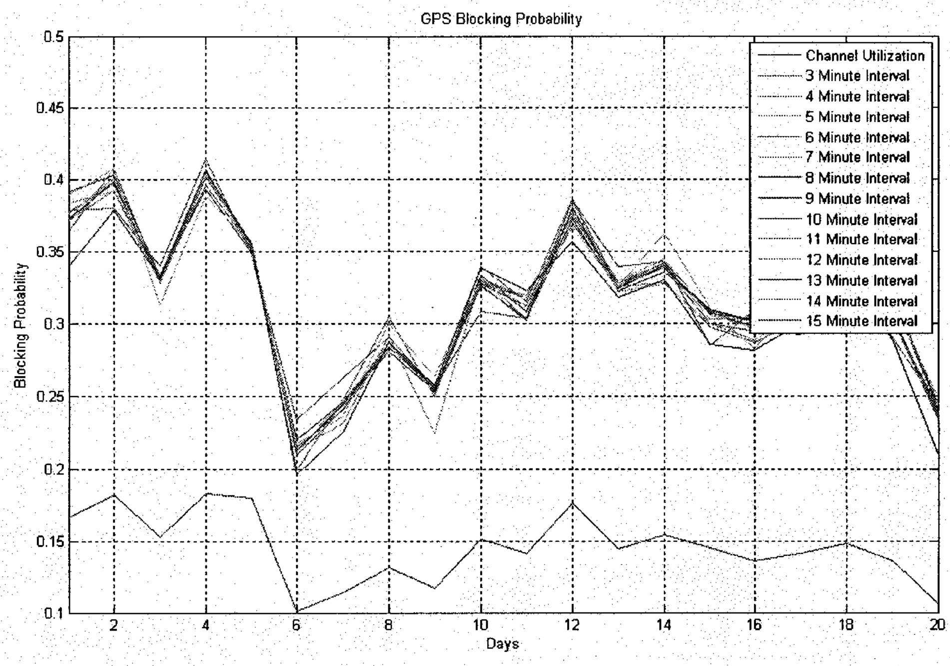


Figure 4.28 GPS Blocking Probability in 20 Days (2 Second Duration)

Thus, the blocking probability of the one second GPS data transmission by the existing radio traffic is about 20%. Meanwhile, that of the two second GPS data transmission is about 30%.

To recommend the GPS data transmission rate and the number of the police units, the channel utilization of the additional GSP data transmission is calculated. We use two assumptions for this recommendation. First, the GPS data transmission duration is one second. Second, the transmission time of the police units are not synchronized, which means that the transmission from each unit may overlap each other. Since the current channel utilization is about 20 % if we assume that the RVD data will be attached to the current data transmission, the 30% more channel may be utilized with the GPS data transmission according to Industry Canada channel loading guidelines (Maximum 50%

channel utilization is allowed in a conventional radio system) [21]. If we assume the GPS data transmission rate for each car to be 1 minute, then the maximum police car units will be 17 units which do not exceed 30% channel utilization (28.3 % ≈ 17 seconds/ 60 seconds). Thus, if the GPS data transmission period for each car is N minute, then the maximum police car units will be 17×N units in the NHDS radio. However, when 17×N units transmit their GPS data without the time synchronization, the GPS blocking probability will be increased approximately to 50%. This is due to the fact that channel utilization will be 50% so data that is not synchronized with existing radio traffic will be lost 50% of the time (Note that in reality, GPS data may block other data transmission instead of the other way around). In other words, half of the GPS data may be lost in the current NHDS radio. This is not recommended. Moreover, according to the result of the cyclic time pattern in this research, the channel utilization may exceeds 50% when it is busy time. To have a reasonable GPS data transmission rate, 10% of channel utilization by the GPS data transmission may be allowed. The minimum interval minute is recommended to be 3 minute and the maximum police units are recommended to be 17 units, where channel utilization is 10% (≈17seconds/ 3 minutes). In this recommendation, the total channel utilization will be about 30% (15% of the current channel utilization + 5% of the RVD attached to the data transmission+ 10% of the GPS data transmission) and the GPS blocking probability is also 30%.

CHAPTER 5

CONCLUSION

Currently, NHDS does not have a method to evaluate the health of its police cruisers without bringing these cruisers into a repair facility. The automated maintenance system for a fleet manager may improve the safety of police cruisers, create the efficient environment of maintenance, and save money by reducing labor. A prototype RVD application is built in the Project54 system so that it suggests some techniques to assist the NHDS fleet manager.

The first proposed step was the OBD-II hardware implementation between the OBD-II in-car network and the IDB network. The chosen OBD-II interface is ELM320, a cost effective integrated circuit. It is used to convert the OBD-II PWM signal to RS232 signal since the Crown Victoria Police Cruiser 2003 uses PWM electrical signal mode.

The second proposed step was the development of the Project54 software module that displays, stores, processes, and simulates sending the vehicle data to the police headquarters. The software module, which is called the OBD-II Scan Application, displays vehicle speed, engine RPM, engine load, engine temperature, fuel level, and vehicle power voltage and stores them in a daily file. The OBD-II Scan Application also reads the DTCs from the vehicle, displays them with a short description, and sends them to the server via a telecommunication tool.

The OBD-II Scan Application processes the vehicle data and sends the vehicle information to the server via a telecommunication tool. 'Vehicle Power Voltage' functionality was implemented to watch the status of the vehicle power voltage because the Project54 system draws a lot of power from the vehicle battery. 'Speed Alert' in the OBD-II Scan Application sends a message to the police headquarters in simulation when the vehicle exceeds 100 mph for five seconds. 'Mileage Estimation' calculates vehicle mileage based on vehicle speed and fuel level information. The difficulty was processing the fluctuating fuel level as the vehicle is moving. The FIR low pass was built to eliminate the high frequency components in order to stabilize the fuel level reading.

The third proposed step was the OBD-II Scan Application testing. The Application was fully tested in simulation. To test the OBD-II Scan Application in the laboratory environment, the OBD-II Simulator was built. The OBD-II Simulator pretends to be the OBD-II network and has functionality simulating various scenarios to confirm the fact that the application is fully functional.

The fourth proposed step was monitoring the NHDS radio traffic. The 'A1 TRP A' channel was monitored for 20 days from February 21st to March 12th in 2006, and both voice and data transmission were recorded. The radio traffic data was processed from the text to the numbers that would be accepted in MATLAB.

The fifth proposed step was modeling the NHDS radio traffic. The radio traffic modeling informs a fleet manager of the possible RVD data transmission on the police radio. Three modeling methods were used: Channel utilization, statistical distribution, and a cyclic time pattern. Channel utilization shows that the 'A1 TRP A' channel is used 15% of the time by both voice and data transmissions. Statistical distribution shows that both the duration time and inter-arrival time of voice transmission are log-normally distributed. Meanwhile, the distributions of both the duration time and inter-arrival time of data transmission are two combined normal distributions. A cyclic time pattern is shown by utilizing the Fourier analysis to recognize the cyclic time pattern of the radio usage. The summed duration and count by each hour of both the voice and data transmission shows the eight hour and daily cyclic time patterns. Indeed, the averaged inter-arrival time by each hour of both the voice and data transmission shows the eight hour and daily cyclic time patterns. Eight hour pattern is caused by the busy hour at 8 A.M. and 4 P.M due to the commuter on the road. Daily pattern is caused since there is daily routine of police work and radio traffic, and the busy 8 hour time pattern.

The sixth proposed step was simulating the possible RVD and GPS data transmission scenarios on the existing radio traffic. Two scenarios were performed to suggest the possible RVD and GPS data transmission. The first scenario was sending the RVD data attached to the current data transmission. The result shows that the additional one second RVD data will be blocked about 58.13% of the time by voice transmissions. Even though there is 58.13% blocking probability, the RVD data attached to the data transmission is recommended in the NHDS radio traffic since it only increases the channel utilization up to 20%. The second scenario was sending the GPS data regularly on the radio traffic. The result shows that the blocking probability by the current radio traffic of the GPS data is deeply related to the channel utilization. No matter how frequent the GPS data may be sent, the blocking probability is proportional to the channel utilization. In 'A1 TRP A' channel, there is about 20% of probability that the one second duration of the GPS data transmission will be blocked. Meanwhile, the two second of the GPS data transmission will be blocked about 30% by the existing NHDS radio traffic. The recommendation is that the maximum 17 units may send the GPS data at 3 minute interval via the NHDS radio. In this way, the channel utilization will be about 30% and the GPS blocking probability is also about 30%.

The goals of this thesis were to suggest the ways of evaluating the health of police cruisers without bringing these cars into a repair facility. The prototype RVD in-car application, or the OBD-II Scan Application, collects, processes, and sends the vehicle data to the server via a telecommunication tool. The radio traffic research gives a few recommendations of the RVD and GPS transmission methods in the NHDS radio.

CHAPTER 6

PROPOSED FUTURE DEVELOPMENT

6.1 RVD System Proposed Future Development

A prototype RVD in-car application is built proposing some techniques in order to assist a fleet manager maintaining police cruisers. The prototype RVD in-car application successfully tested in simulation and it is expected to send vehicle information via the NHDS radio. According to the recommendation, the NHDS radio has sufficient bandwidth to send the RVD data. However, to complete a whole RVD technology in the Project54 system, a distributed RVD system is suggested in the future.

Currently, the Project54 system contains two distributed components which are a remote agent and a simple remote server. The remote agent is the OBD-II Scan Application which is a current prototype in-car application. The remote server takes care of data interpretation, timer, parsing the messages. It creates a simple text file displaying the messages from the remote agent. There is need to develop two other distributed components: a client application and data server. Two additional components will complete the RVD application in the Project54 system.

A RVD system design is suggested as a distributed architecture [3]. Main distributed components of RVD are client application, remote server, database server, and remote agent. Client application for a service technician requests vehicle diagnostics data from remote agents via a remote server which stores it as a new task in a database server (Figure 6.1).

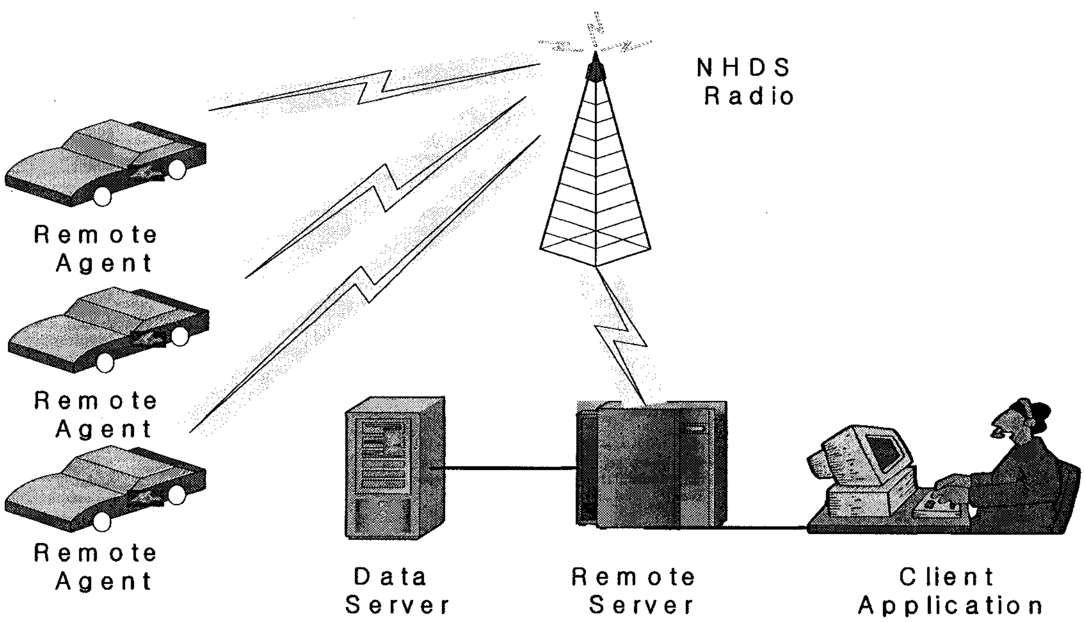


Figure 6.1 A Distributed RVD System

Two components are missing in the current Project54 system: client application and database server. The client application would be an interactive GUI interface for users to request vehicle diagnostics data from the remote server. The data server would be the storage to manage all vehicle diagnostics data from remote agents and a remote server. A large amount of data such as one vehicles' lifetime would be stored in a data server for future vehicle analysis.

As an aspect of RVD contents, three different scenarios would be categorized as notification, real-time data monitoring, and periodic log [3]. Notification is critical information to be sent immediately to a technician. Real-time data monitoring is used to observe vehicle data via any wireless communication tool when the vehicle is on the road.

The periodic log stores long term vehicle performance data for a technician to inspect vehicle status. Three different scenarios are introduced in detail below.

Notification could be a key factor of passenger's safety. Airbag deployment notification is one factor commonly implemented on the RVD system. DTC alert is not critical as airbag deployment notification, but the main advantage of DTC alert is that there will be no wasting time for technician to diagnose the malfunction of the vehicle if the detected DTC is sent to technician before the vehicle arrival. Furthermore, technicians might be better prepared to fix it when the vehicle gets there.

Real time data monitoring would collect real time vehicle data when the vehicle is moving and allows the mechanic to become a remote worker diagnosing the vehicle [7]. In this case, the vehicle can be on the highway instead being in the service center area where vehicle malfunctions can not be detected.

We would estimate the technical lifetime of a vehicle system with the periodic log, tracking the complexity of vehicle performance. This RVD data management may prevent a vehicle from degradation and fatigue. It could distinguish different types of faults by data analysis. There are two data analysis tasks: technical lifetime estimation and predictive diagnosis [8].

The technical lifetime estimation calculates the lifetime of subsystem in a vehicle using multiple variables. The current estimation depends only on mileage information. The technical lifetime estimation is useful technique because it gives better estimation than mileage information alone. For instance, currently only mileage information is used to estimate the lifetime of engine oil. However, the technical lifetime estimation may utilize engine oil quality, engine oil level and so on. In this way, this technical lifetime estimation would be more accurate than the estimation based on the mileage information alone.

Predictive diagnostics is recognizing a symptom that is learned from the previous experience before actual breakdown of a vehicle. Predictive diagnosis is the short-term prediction of faults based on the analysis of recorded vehicle signal sets. First, a fleet of vehicles' signals are recorded all the time along their state and environment. Second, if a fault occurs, the RVD server saves a fault specification from the vehicle data. If the same fault occurs in different vehicles or in the same vehicles, the fault identification accuracy is increased. Predictive diagnostics is also useful approach to maintain vehicles as well as technical lifetime estimation.

At last, the RVD application in the Project54 system would be nice to diagnose not only the vehicle, but also the police equipment connected to the Project54 system. In this way, we would differentiate the Project54 RVD application with the other commercial RVD systems.

6.2 Radio Traffic Research Future Development

The 'A1 TRP A' channel is analyzed in this thesis. In the future, multiple channel analysis is suggested to generalize the characteristics of the radio traffics in New Hampshire. The 'A1 TRP A' cannot represent the whole radio traffic of the NHDS radio.

The long term radio traffic monitoring is also required. The longer the radio traffic is monitored, the more information may be obtained. First of all, weekly or monthly cyclic time pattern may be recognized if we monitor the radio traffic for enough time to identify them. Second, we have the more chance to see the abnormal behavior of the radio traffic. This incident may occur during emergency accident or a disaster. It would be useful to analyze the abnormal radio traffic activity comparing with the normal radio traffic activity. With the analysis of the disaster scenarios, we could prepare for the future disaster case.

The radio traffic simulation program would be great tool to simulate all sorts of scenarios in the NHDS radio. Currently, there is no such a program to simulate the NHDS radio traffic. Depending on the number of police cruisers, the number of retransmitting antennas, or the position of retransmitting antennas, as well as the disaster scenarios, the simulation program would help the NHDS predict the radio volume.

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